INTRODUCTION

Photovoltaics (PV) using thin film CdTe as a photon absorber have been studied for several decades. CdTe was long recognized for its potential to surpass the conversion efficiencies of conventional silicon solar cells based on bandgap matching to the Shockley Queisser limit. However, progress was slow in reaching this protentional with best laboratory cell efficiencies climbing from ~9% in 1976 to 16% in 1993. A virtual plateau in efficiency followed for the next 20 years before the efforts of First Solar and GE Global Research (now one entity) helped push the efficiency to 22.1% at the time of this review by the First Solar company. First Solar are the leading commercial manufacturers of thin film photovoltaics having recently introduced their Series 6 offering in excess of 17% efficiency at the module level.

CdTe PV can be constructed under two device architectures (Figure 1); the PV thin films can be deposited onto a substrate material in the general order electrode, p-type CdTe absorber, n-type buffer layer, electrode or the reverse order.
transparent substrate material, transparent electrode, n-type buffer, p-type CdTe absorber, and electrode. The latter is the preferred route for several optimal device performance reasons and necessitates the use of an optically transparent superstrate material and initial electrode layer. The CdTe in superstrate configuration relies on the following factors, among others, to achieve high conversion efficiency. Firstly, a substrate, electrode (front contact), and n-type buffer which are optimized to transmit photons with an energy above the absorber bandgap. Secondly, a chlorine heat treatment of the CdTe and thirdly, an Ohmic (back) contact to the CdTe. The majority of CdTe PV research and all module manufacturing to date has exploited the superstrate configuration.

CdTe has a high electron affinity of around 4.4 eV, which together with its energy gap of around 1.45 eV, means that many materials that might be considered good conductors and thus good back contacts, tend to form Schottky barriers (see Figure 2A) which oppose the flow of current into the solar cell.

The exceptions to this are metals with very high work functions which form Schottky contacts with small barriers and can thus act effectively as Ohmic-like contacts at normal working temperatures (eg, gold and palladium). This difficulty has been noted many times (eg, Wald (1977), Fahrenbuch (1987). Demtsu and Sites (2006) gave a good description of how forward-bias rollover can occur due to a rear contact barrier.

Before we consider the multitude of possible back contacts, it is important to note that the chemistry of the materials at and near the back contact needs to be considered as much as the fundamental physical properties of CdTe and its back-interface material. The interface must minimize photogenerated carrier recombination. The simplistic approach of matching the valence band positions through knowledge of a value of the electron affinity and the bandgap, although useful, can also be misleading if the chemistry leads to interlayer compound formation, or interfacial states lead to Fermi level pinning.

The back contact issue is not unique to CdTe—it is also believed to be a limiting factor in some other thin film solar cell technologies; such as the perovskite structure materials (“ABX₃” which achieve high efficiency but are not yet a well-established commercial technology), and other thin film solar cell technologies using chalcogenides (mainly CIGS and kesterites). The back contact is also commonly referred to as the hole transport material (HTM) in perovskites.

**Figure 1** Typical superstrate (left) and substrate (right) CdTe solar cells configurations

**Figure 2** Generalized valence band alignment diagrams for the back contact to CdTe solar cells. (A) To metals—large hole barrier. (B) Generic semiconductor back contact with large hole energy barrier. (C) Generic idealized semiconductor back contact with small hole barrier and electron reflection character.
and is one factor limiting both efficiency and long-term stability\(^\text{15}\) of perovskite devices.

Many CdTe back contact technologies utilize small amounts of copper to increase the p-type doping level. This element can be delivered as a metal layer with a thickness of a few nanometers, or as a copper compound, such as Cu$_x$Te. Thicknesses of copper-containing layers is often well below 10 nm. However, it is known that as well as providing p-type doping copper introduces deep levels\(^\text{16}\) into the CdTe, and that copper is highly soluble in CdTe.\(^\text{17}\) Copper re-distribution within a polycrystalline solar cell is a complex process. However, the record efficiency cells have almost unanimously utilized copper as part of their back contact technology.

The challenge of creating an optimum back-surface contact for CdTe has been a goal of many research teams for decades and has been reviewed before, for example by McCandless and Sites (2011)\(^\text{18}\) and Kumar and Rao (2014).\(^\text{19}\) This review seeks to integrate post-2014 literature into a comprehensive view of the subject.

Back contact technologies for polycrystalline CdTe on flexible substrates have recently been reviewed by Znajdek et al (2019)\(^\text{20}\). A small number of back contact technologies were reviewed in this paper, before copper, molybdenum, and silver (full coverage of silver and a mesh) were used in bending test experiments. In the case of flexible cells, adhesion and matching of thermal expansion coefficients are even more crucial than when CdTe is deposited on rigid substrates.

In reviewing the literature for back contacts to CdTe, it seemed prudent to the authors to group the many materials that have been used into categories. However, it is acknowledged that the categorization used here is not unique. Neither does it adequately describe the multiple materials and processes used in many cases. Nevertheless, it can be a useful approach. The list of categories used is given in Table 1.

In this analysis, it is often difficult to do like-for-like comparisons. Devices with deliberately grown Cd(Se,Te) absorbers will have a different point at which solar cell performance is strongly limited by the back contact, due to effects such as different front contact, carrier lifetimes, and grain boundary passivation. Consequently, such devices are largely excluded from the analysis, except when little or no information is available for a back contact material with a CdTe absorber. CdTe n-type absorber solar cells are not included in this review due to the comparatively little literature available. Differences in the front contact are also present. Often the difference in the front contact will largely affect the short-circuit current. Therefore, power conversion efficiency (PCE), open-circuit voltage ($V_{oc}$), and fill factor (FF) will be given more consideration.

In some cases, it is arguable as to whether a process treatment also can be classified as a back contact material. One important example is the ubiquitous chlorine heat treatment (CHT) (most commonly using CdCl$_2$ or chlorine diffusion). If this treatment leaves the back-surface rich in chlorine, then chlorine can be said to be a constituent of the back contact material, even though a further material will be required for electrical contact.

A second classification of back contact materials is whether the process is free of copper (or other potentially mobile dopants) or not. As mentioned, a small amount of copper has been an integral part of many of the back contact technologies developed for CdTe solar cells. Copper is commonly used to dope CdTe p-type to a suboptimal doping level in the range $10^{14}$ to $10^{15}$ cm$^{-3}$. However, the presence of “excess” copper is also associated with long-term cell degradation.\(^\text{21}\) Therefore, many of the copper-containing processes have undergone trials with very restricted amounts of copper to optimize performance, but also to minimize long-term performance drops. Other approaches have sought a copper-free contacting technology.\(^\text{22}\) It is not within the scope of this paper to review all the literature on copper usage in back contact technologies, itself the subject of many articles.\(^\text{23}\)

A third possible classification is whether the contact material(s) are transparent. (It is noted that CdTe is not transparent in the visible spectrum for absorber layers thick enough to produce high PCE). As shown in Figure 1 the superstrate

| Category | Examples |
|----------|----------|
| Group IV | a-Si:H, a-Si$_1_x$C$_x$:H, Bi-ROGO |
|          | CuCNi, Cu$_x$Te/SWCNT, graphene:B, SWCNT, graphite |
| Metal    | AgNW/ITO, Cu, Cu NW, Mo |
| Metal pnictide | Mo$_x$N$_x$, Zn$_x$N$_x$, Ni$_x$P |
| Metal oxide | Cu$_x$O/Au, Cu$_x$O |
|           | ITO, Cu/Au/ITO, MoO$_x$, Cu$_x$O$_2$ |
|           | NiO (p-type), V$_2$O$_5$, WO$_3$, ZnO:Al |
| Metal selenide | VSe$_2$, TiSe$_2$, (BaCuSeF, SrCuSeF) |
| Metal sulfide | CIS, CIS:N, CuS, Cu$_x$Zn$_x$S, Fe$_x$Te$_2$, (Fe,Ni)$_x$S$_2$ |
| Metal telluride | Cu$_x$Te, Cu$_x$TeNi, Hg$_x$Te:Cu, NiTe$_2$, SnTe:Ni |
|           | ZnTe:As, ZnTe:Cu, ZnTe:Cu/ITO, ZnTe:N, ZnTe:Sb, ZnTe:Si |
| Telluride, other | (N$_2$H$_3$)$_2$CdTe$_2$, Cs$_x$CdTe$_2$, K$_x$CdTe$_2$, Na$_x$CdTe$_2$, As$_x$Te$_2$, Sb$_x$Te$_2$, Bi$_x$Te$_3$ |
| Metal halides and perovskites | CuI, BaCuSeF, SrCuSeF, BaCuSF, BaCuSF/ITO, MAPb(Br$_{1-x}$I$_x$)$_3$ |
| Organic and carbon containing | CoPC/Au, CuSCN/Au |
|          | P3HT, PCBM, PEDOT, Pentacene, PFO, Ppy, spiro-OMeTAD |
configuration transmits photons to the absorber layer via the transparent substrate, front contact, and n-type buffer. However, for some applications such as tandem\textsuperscript{24} and bifacial solar cells, a contact with good visible and near-infrared transparency to at least 800 nm is also required. A third technology which requires NIR transparent back contacts is a nonconventional PV-thermal (PVT) solar cell in which the transmitted NIR radiation is used elsewhere, including by focusing NIR onto a heat collector such as an evacuated tube. For these architectures, any use of narrow bandgap materials, or metals thicker than 10 nm or so, at the back surface will reduce substantially transmission of subbandgap radiation through the CdTe. If back contact materials are extremely thin, or do not have close to 100\% coverage of the back surface, then a binary transparent/opaque description could be misleading.

The maximum processing temperature during the deposition of back contacts needs to be considered. Although CdTe has a high melting point (1050°C\textsuperscript{17}), some elements can diffuse quickly through CdTe. In polycrystalline CdTe, diffusion along grain boundaries can be much faster than bulk diffusion (eg, copper\textsuperscript{21} and sulfur\textsuperscript{25}). Grain boundary passivation from the CHT process can also be affected by loss of Cl\textsubscript{2} at very high subsequent processing temperatures.

The metal(s) used as the final contact also influence PCE in some cases, as well as sometimes making the devices more or less stable over time. This can be through the formation of Schottky barriers or by diffusion into or through the CdTe.

To maximize solar cell PCE, resistive heating losses need to be minimized. If a back contact material has a low lateral conductivity, then a more conductive layer is required on top to avoid excessive series resistance. Conductive materials dominated by hopping conductivity, such as many organic compounds, have very low mobility values compared to relatively large-grained inorganic conductors with delocalized conduction or valence bands. These low mobility materials will always require a more conductive layer on top, or a metal grid/mesh/network with low mean spacing, so lateral transport to a metal is only a short distance.

Although it has been stated that band offsets are of limited use, the concept is of some use in choosing materials to study. Directly measuring band offsets is difficult. XPS studies can give a picture of offsets relative to vacuum level, but less so when buried within a device structure. Analysis of temperature-dependent forward-bias rollover in J-V curves is one method of determining an effective back contact barrier in situ and inferring valence band offset (VBO).

Recently, the concept of initial Fermi level offset (IFLO) has been promoted (Liyanage et al (2019)\textsuperscript{27}) through extensive 1-D modeling (using SCAPS\textsuperscript{28}); this concept might allow doping levels in CdTe and the back contact material to be accounted in a better manner than just using the VBO.

## 2 | SURFACE PROCESSING BEFORE BACK CONTACTS

### 2.1 | Chemical treatments

Chemical treatments prior to back contact deposition have been reviewed by Kumar and Rao (2014).\textsuperscript{19} The as-grown CdTe can be subject to chemical modification by etching prior to back contact deposition. It is noted that the presence of many grain boundaries in polycrystalline CdTe means that some etches which might provide a beneficial surface condition on single-crystal CdTe might increase recombination at grain boundaries on polycrystalline CdTe.

The first etch we mention is an etch using potassium chromate and sulfuric acid (chromate etch) used on p-type bulk-grown CdTe. Anthony et al (1982)\textsuperscript{29} measured contact resistances of 0.1-0.5 Ω cm\textsuperscript{2} using Cu-Au or Au on a K\textsubscript{2}Cr\textsubscript{2}O\textsubscript{7}:H\textsubscript{2}SO\textsubscript{4} etched surface—significantly lower than when a bromine-methanol (Br-Me) etch was used. This etch leaves the surface Te-rich with the presence of some TeO\textsubscript{2}.\textsuperscript{30} Rimmaudo et al (2017)\textsuperscript{31} attempted to form a layer of Cu\textsubscript{x}Te through a process including Br-Me etching before Cu/Au deposition. The Br-Me etch allowed less Cu to be used, giving a “more optimal” doping and improving device stability. Improved performance was also attributed to the reduction in grain roughness observed in AFM studies. Awni et al (2018)\textsuperscript{32} and (2019)\textsuperscript{33} also showed grain roughness reduction when using a hydrogen iodide in methanol etch. Additionally, a reduction in back contact barrier height was observed after etching.

Another common etch is a nitric-phosphoric (NP) etch.\textsuperscript{34,35} Both Br-Me and NP etches leave the surface Te-rich; the NP etch leaves a thicker Te-rich layer. A Te-rich surface is believed to be beneficial for back contact formation.\textsuperscript{36} The NP etch preferentially etches grain boundaries and can be overdone, leading to pinholes. Proskuryakov et al (2007)\textsuperscript{37} studied various NP etch conditions using both solar cell J-V characteristics and variable temperature admittance spectroscopy. Short etch times mostly affected the back surface, but longer etch times also caused changes at grain boundaries. Major et al (2014)\textsuperscript{38} (Liverpool University) used N-P etches before and after chloride treatments in a study of chloride treatments other than CdCl\textsubscript{2} (MgCl\textsubscript{2}, NaCl, KCl, and MnCl\textsubscript{2}).

### 2.2 | Electron reflectors

Hole transport is required at the back contact of a superstrate CdTe solar cell. Electrons which reach the back contact interface are likely to recombine. Hsiao and Sites\textsuperscript{39,40} at Colorado State University studied strategies for providing interfaces with an electron reflecting character, reducing interface
recombination. The introduction of a material with a small valence band offset and a larger conduction band (likely higher energy gap) could provide a means for hole transport, while band bending at the interface could lead to an electric field tending to repel electrons from the interface ("reflection"). A generic alignment of conduction and valence bands for an electron reflector back contact is shown in Figure 2C. Hsiao and Sites work suggested that PCE 19%-20% was possible with a 1 µm thick absorber if an electron reflector was used in a structure which also had good optical reflection. ZnTe is an early example of a material with the expected band alignment expected to produce electron reflection when deposited on CdTe. More recently other materials including CdMgTe have been studied as potential electron reflectors.

3 | METAL BACK CONTACTS

Metals tend to form Schottky contacts to p-type CdTe, as indicated by Ponpon (1985) (see Figure 2A). The lowest barriers are formed with high work function metals, nickel (see nickel telluride contacts), and gold, which are a closer match to the electron affinity plus bandgap of CdTe. Gold and platinum are too expensive for use in modules but can be very useful in laboratory studies. Of the economically viable metals, only nickel (and carbon) has work functions sufficiently high to avoid very large Schottky barriers. Nickel in CdTe forms a deep acceptor level. One example paper by Wei Xia et al (2014) shows the effect of using Ni on as-grown CdTe surfaces: PCE is improved by NP etching before Ni deposition, or by using Te or Te/Cu interlayers before Ni deposition. For long-term stability, the diffusion of metals into CdTe must be considered.

In many cases, tellurides can form at the interface when metals are deposited. The effect of the tellurides on the interface needs to be considered (see also the section on telluride contacts). Even less reactive metals such as gold can form a telluride at the interface. Odkhuu et al (2016) performed electronic structure calculations on the Schottky barriers formed between CdTe and Cu, Pt, and Al when the CdTe surface was Cd-terminated and Te-terminated. Different barrier heights were obtained for the different surface terminations, and barrier heights were found to be heavily influenced by metal-induced gap states. Li et al (2017) also studied Schottky barrier heights for Al, Ag, Au, Cu, and Ni. The lowest Schottky barriers determined were Ni (0.66 eV) and Au (0.44 eV).

4 | TELLURIUM AND TELLURIDE BASED CONTACTS

In this category the following materials that have been used for back contacts will be discussed: tellurium, undoped and doped copper tellurides, mercury telluride, nickel telluride, tin telluride, with a more extensive discussion on zinc telluride and its doping.

4.1 | Tellurium as a back contact

Tellurium is one natural choice of back contact, as the element is already present in the CdTe absorber. The melting point is much lower than CdTe at around 450°C. Tellurium is a (bulk) p-type degenerate semiconductor with reasonably high conductivity that can be increased by doping (copper) and has a low VBO to CdTe. Niles et al (1996) showed a PCE value of 12.1% with an evaporated Te back contact ( Voc 740 mV, Jsc 22.4 mA cm−2 FF 65.4%), slightly outperforming their control process which involved etching to obtain a Te-rich surface. A near contemporaneous XPS study by Niles et al (1995) had found a valence band offset of 0.26 ± 0.1 eV between the evaporated Te and CdTe. Kraft et al (JAP 2003) found a valence band offset of ~0.5 eV using XPS between CdTe and Te prepared by chemical etching of CdTe. Moffet and Sampath (2017) published XPS characterization work on Te thickness variations on CdTe. Temperature-dependent J-V curves showed the back-barrier height decreasing as Te thickness increased from 2 nm to 8 nm, reaching bulk values at 50 nm.

Tellurium back contacts were one component of the revised structure (Munshi et al (2018) (Colorado State University) used to achieve a cell with 18% PCE. They also used a MgZn1−xO buffer, thick CdTe, and front AR coating. The back contact barrier height was suggested by Alfadhili et al (2019) to be smaller for Te than for ZnTe.

 Provision of a deposited Te layer has produced higher PCE than a Te-rich layer produced by etching as the Te layer thickness is more controllable in a deposition process, as well as avoiding the possible creation of etched pinholes and affecting passivated grain boundaries.

4.2 | Copper telluride

Copper telluride introduces copper which will dope CdTe and provide the back contact. Ferekides et al (1997) showed PCE values approaching 15%. They found that a thin (50 nm) copper telluride layer produced maximum Voc and FF (best Cu,Te/Mo back contacted cell: PCE 14.9%, Voc 838 mV, Jsc 23.77 mA cm−2, FF 74.9%—NREL certified). McCandless et al (2003) investigated the different phases of copper telluride formed on the back surface following the deposition of different thicknesses of copper. Yan et al (2005) at NREL published on the use of copper telluride. In this case, HgTe was used as well, forming HgCdTe at the back surface, so the role of copper telluride itself is more difficult
to extract. It was also investigated by Avachat (2005)\textsuperscript{56} of the University of Central Florida, Wu et al (2007),\textsuperscript{57} and Zhou et al (2007),\textsuperscript{58} who found that the dominant phase of copper telluride was thickness dependent, becoming more copper rich with increasing thickness. The maximum PCE (12.9\%, $V_{oc}$ 797 mV, $J_{sc}$ 22.7 mA cm$^{-2}$, FF 71.3\%, and $R_s$ 1.09 Ω cm$^2$) was obtained at a copper telluride thickness of 10 nm (mixed CuTe and Cu$_{1.4}$Te phases), while at a thickness of 60 nm, the PCE dropped to 12.1\% (single-phase Cu$_{1.4}$Te). At a thickness of 130 nm, the less thermodynamically stable Cu$_2$Te phase dominated but at a thickness of 80 nm, the PCE dropped to 12.1\% (single-phase Cu$_{1.4}$Te). More recently, Moore (2017)\textsuperscript{59} studied CdTe/ZnTe interface,\textsuperscript{60} but the ZnTe is also expected to reduce or slow diffusion of copper into the CdTe.\textsuperscript{61}

Back surface processes that deposit thin layers of copper on Te-rich surfaces also form copper tellurides and, in some cases, the formation of copper tellurides can act as a means of consuming excess copper which could otherwise diffuse through the CdTe. It has also been suggested that copper deposited on top of other layers (specifically ZnTe) can diffuse via grain boundaries to form copper tellurides at the ZnTe-CdTe interface,\textsuperscript{60} but the ZnTe is also expected to reduce or slow diffusion of copper into the CdTe.\textsuperscript{61}

### 4.3 | Mercury telluride and Hg$_{1-x}$Cd$_x$Te

Mercury (II) telluride (HgTe) is a semi-metal rather than a semiconductor. It has a relatively high conductivity compared to CdTe. Hg$_{1-x}$Cd$_x$Te alloys are stable with a cubic crystal structure with a nearly constant lattice parameter for all compositions.\textsuperscript{62} The low energy gap means that the material is not transparent in the near infrared (NIR) until the Cd composition exceeds around 70\%. Hg-Te bonds are relatively weak compared to Cd-Te bonds leading to Hg diffusion at moderately high temperatures.

Janik and Triboulet (1987)\textsuperscript{62} showed that HgTe deposited by close space sublimation could provide a low resistance Ohmic contact to CdTe and Hg$_{1-x}$Cd$_x$Te, due to good work function matching, but did not fabricate solar cells. This work was extended by Zozime and Vermeulin (1988)\textsuperscript{63} to analyze specific contact resistance accounting for doping level. Specific contact resistance remained at 15-500 Ω cm$^2$ for material of resistivity 1.5-45 kΩ cm but dropped to 7 Ω cm$^2$ for ~70 Ω cm resistivity material.

A paste made of graphite mixed with HgTe (often copper doped) has been used extensively\textsuperscript{64,65} and probably was the material used by Britt and Ferekides (1993)\textsuperscript{3} in their 15.8\% PCE device ($V_{oc}$ 843 mV, $J_{sc}$ 25.1 mA cm$^{-2}$, FF 74.5\%). A CuTe:HgTe doped graphite paste (then silver paste) was used by Wu et al (2001)\textsuperscript{66} in NREL’s then record 16.5\% PCE device ($V_{oc}$ 845 mV, $J_{sc}$ 25.9 mA cm$^{-2}$, FF 75.5\%), this device had cadmium stannate/zinc stannate front contacts.

Hanafusa et al (2001)\textsuperscript{67} used a wide range of materials to “dope” graphite pastes used as back contacts. The added materials that resulted in PCE over 12\% included the silver halides (AgCl and AgF), silver telluride, silver phosphate and molybdate, as well as nickel phosphide and telluride, and zinc phosphide. Lead-containing additives reduced PCE, as did NiO. Compounds containing Bi and Sb were also tried.

### 4.4 | Zinc telluride

Zinc telluride (ZnTe) is a semiconductor with an ambient temperature energy gap of around 2.2 eV,\textsuperscript{68} higher than the energy gap of CdTe. ZnTe has the same cubic crystal structure as CdTe. The high bandgap means that ZnTe is not suitable for use as a single absorber in a high PCE solar cell. ZnTe can be doped p-type by pnictides (N,\textsuperscript{69} P,\textsuperscript{70} As,\textsuperscript{71} Sb,\textsuperscript{72} and Bi) and by copper. The electron affinity of ZnTe is such that the valence band offset to CdTe is very low.\textsuperscript{73} This allows hole transport to a metal contact with smaller barriers than for those created by directly contacting CdTe with metals. There are also suggestions that ZnTe could act as an electron reflector if the recombination rate at the interface is sufficiently low (see also section on electron reflectors).

ZnTe was the contact material to CdTe for AMETEK’s late 1980s world record ITO/CdS/CdTe/ZnTe/Ni solar cell which achieved PCE 11\%. Copper-doped ZnTe on CdTe has been studied since before 1992 (Mondal et al (1992)\textsuperscript{74} at the University of Delaware) and by many groups since. By 2015,

| Reference | Material | $V_{oc}$ (mV) | $J_{sc}$ (mA cm$^{-2}$) | FF (%) | PCE (%) | $R_s$ (Ω cm$^2$) |
|-----------|----------|--------------|-------------------------|--------|---------|-----------------|
| Ferekides et al (1997)\textsuperscript{74} | CdS/CdTe/Cu$_x$Te/Mo | 838 | 23.8 | 74.9 | 14.9 | - |
| Xia et al (2014)\textsuperscript{44} | CdS/CdTe/Cu | 820 | 22.2 | 77.6 | 14.1 | - |
| Zhou et al (2007)\textsuperscript{58} | CdS/CdTe/NP etch/Cu/C-paste/Ag | 797 | 22.7 | 71.3 | 12.9 | 1.09 |
| Kim et al (2018)\textsuperscript{236} | ITO/CdS/CdTe/Cu$_2$Te | ~800 | 25.5 | 59 | ~12 | 6.5 |
| Moore (2017)\textsuperscript{59} | CdS/CdTe/Cu/Te/Ni | 801 | 22.4 | 72.4 | 13.0 | 1.1 |
| Moore (2017)\textsuperscript{59} | MgZnO/CdTe/Cu/Te/Ni | 853 | 25.7 | 77.9 | 17.1 | 0.6 |
NREL reported a 16.4%\textsuperscript{75} PCE, although the focus of this paper was the fact that the CdTe solar cell was flexible.

Amin et al (2002)\textsuperscript{76} tried ZnTe and Cd\textsubscript{0.7}Mg\textsubscript{0.3}Te:N back contacts to thin (1 µm CdTe) solar cells obtaining 8.3% PCE (low FF of 49%) for ZnTe/Cu/Ag contacted devices. Chen et al (2019)\textsuperscript{77} studied ZnTe:Cu back contacts to CdTe using a CdSe buffer layer (ITO/ZnO/CdSe/CdTe/ZnTe/Cu/Au structure). Although an improvement over the Au only back contact was observed, the maximum PCE was 6.38%.

A ZnTe-based back contact layer still requires metallization. Gessert et al (2014)\textsuperscript{78} studied the contact properties of titanium on doped ZnTe. Metal-semiconductor contact resistance is a somewhat neglected area of study in the context of CdTe solar cells (and associated materials): a comprehensive review is overdue but is not within the scope of this article. Gessert et al\textsuperscript{78} concluded that the likely range of contact resistance of Ti to ZnTe was 0.1-0.5 Ω cm\textsuperscript{2}. This is orders of magnitude more than what can be achieved with rare metal contacts such as between Au on Pd on >10\textsuperscript{19} cm\textsuperscript{−3} p-doped ZnTe (5 x 10\textsuperscript{−6} Ω cm\textsuperscript{2} – Ozawa et al (1994)\textsuperscript{79}).

Kurley et al (2017)\textsuperscript{80} used liquid chemistry to modify the rear surface of CdTe solar cells. This approach is categorized here with the ZnTe papers for convenience but is really a distinct approach. The best PCE (12.7%) resulted from forming an interfacial layer of (N\textsubscript{2}H\textsubscript{5})\textsubscript{2}CdTe\textsubscript{2} on top of CdTe. This was a marginal PCE gain over their control device with V\textsubscript{oc} improved from 684 mV (control) to 726 mV ((N\textsubscript{2}H\textsubscript{5})\textsubscript{2}CdTe\textsubscript{2} treated). Another contact used by Kurley\textsuperscript{81} was to spin-coat ZnTe:Sb onto CdTe (best cell PCE 6.4%).

It is clear from Table 3 that in order to obtain high PCE either the back contact process must contain Cu or the CdTe is already heavily p-type doped (Oklobija et al (2019)\textsuperscript{71} used arsenic doping).

Cd\textsubscript{0.7}Mg\textsubscript{0.3}Te was recently used by Feng et al (2020)\textsuperscript{82} to increase the conduction band offset at the back interface while not creating a large VBO. A Cd\textsubscript{0.7}Mg\textsubscript{0.3}Te electron reflection layer gave PCE 13.4% (V\textsubscript{oc} 804 mV, J\textsubscript{sc} 23.1 mA cm\textsuperscript{−2}, FF 72%) after annealing at an optimum temperature of 425°C. Te/Cu was deposited on the CdMgTe before Au contacts were deposited.

Unencapsulated cells were thermally stable to around 200°C, but exposure to water vapor led to reversible degradation.

Other transition metal tellurides have been studied as potential photovoltaic technology materials. There has been little or no experimental work on using them with CdTe absorber solar cells. MoTe\textsubscript{2}, a layered material,\textsuperscript{86} has been numerically modeled as a back contact,\textsuperscript{87,88} but we have not found any experimental data on at the time of publication other than the work of Dhar et al (2015)\textsuperscript{89} concerning the Mo/CdTe interface and the older work of Löher et al (2000)\textsuperscript{90} on MBE-grown CdTe/MoTe\textsubscript{2} interfaces.

MnTe\textsubscript{2}, a p-type semiconductor, was tried by Shen et al (2010)\textsuperscript{91} as a back contact in substrate configuration devices. MnTe\textsubscript{2} was formed on Mo by annealing of Mn/Te bilayers and by direct evaporation of MnTe\textsubscript{2}. Devices showed severe forward-bias rollover with V\textsubscript{oc} limited to about 500 mV.

4.6 | Group IV tellurides

Group IV tellurides are possible materials for back contacts. There are no known experimental studies of silicon telluride (Si\textsubscript{2}Te\textsubscript{3}) or germanium telluride back contacts and only one numerical study\textsuperscript{92} using AMPS software\textsuperscript{93} on CdTe solar cells.

Tin (IV) telluride is a narrow gap semiconductor with a rock-salt structure, which might remain in a zinc-blende structure for very thin layers grown on CdTe.\textsuperscript{94} Weng et al (2018)\textsuperscript{95} experimented on solar cells with eight different contact structures all including a final 100 nm thick Ni layer. Half of the structures included a light NP etch (intended to remove oxides), and half had a longer NP etch (to produce a Te-rich surface). Maximum PCE was obtained with a structure using a light NP etch, 60 nm ZnTe followed by 5 nm of copper then 40 nm SnTe before the metal contact was deposited. This cell gave 14.6% PCE (V\textsubscript{oc} 841 mV, J\textsubscript{sc} 24.7 mA cm\textsuperscript{−2}, and FF 70.2%). T. Shu et al (2019)\textsuperscript{96} also used SnTe/Ni back contacts (PCE 13.1%, V\textsubscript{oc} 782 mV, J\textsubscript{sc} 24.6 mA cm\textsuperscript{−2}, and FF 68%).

Lead telluride (PbTe) has been suggested as a back contact material in 1D simulation studies.\textsuperscript{97} XPS has suggested a low VBO between PbTe and CdTe(111) surfaces.\textsuperscript{98} It was expected that a two-dimensional electron gas can form at the PbTe/CdTe (111) interface, probably increasing recombination but no experimental solar cell results were available until the work of Swartz et al (2019).\textsuperscript{99} They found that despite indications that the CdTe/PbTe:TI contact was Ohmic, that the PbTe:TI layer also appeared to be photoconductive. Cells were shunted—limiting the PCE to 9%. The low bandgap of PbTe (~0.29 eV) means that the material is opaque in the NIR and visible bands. Thallium is extremely toxic and not produced in large quantities.

4.5 | Nickel telluride and other transition metal tellurides

Nickel telluride (NiTe\textsubscript{2}) is a semi-metallic material with intrinsic resistivity 10\textsuperscript{−7} to 10\textsuperscript{−6} Ω cm. It crystalizes with a CdI\textsubscript{2}-like structure\textsuperscript{83} and is stable even with a few percent tellurium deficiency. Although nickel is a well-used contact metal, studies of NiTe\textsubscript{2} are less common. Rotlevi et al (2001)\textsuperscript{84} and Dobson et al (2002)\textsuperscript{85} published studies of electroless NiTe\textsubscript{2} contact formation to CdTe. A PCE of ~10% was obtained (V\textsubscript{oc} ~ 800 mV, J\textsubscript{sc} ~ 25 mA cm\textsuperscript{−2}, FF ~ 65%).
Because Sn and Pb doping in CdTe can cause compensation effects and potential carrier lifetime reduction, it is suggested that research in this area proceed with caution—if sufficient group IV related recombination centers develop over time or with subsequent thermal processing, solar cell performance might be impacted. Group IV and Group V telluride back contact results are summarized in Table 4.

4.7 | Group V tellurides: arsenic, antimony, and bismuth tellurides

Tellurium does not form a stable compound with nitrogen, and phosphorus telluride bonds are weak. Arsenic (III) telluride, antimony (III) telluride, and bismuth (III) telluride are all stable compounds. Nitrogen, phosphorus, arsenic, and antimony all dope CdTe p-type.

Sb$_2$Te$_3$ is a layered narrow-gap semiconductor with van der Waal’s bonding between layers. This forms an intermediate layer. The work function of Sb$_2$Te$_3$ is 5.8 eV, in theory a very good match to p-type CdTe. Sb excess is likely to dope CdTe p-type. Sb$_2$Te$_3$ contacts have been reported twenty years ago (Romeo et al (2000) $^{107}$). Sb$_2$Te$_3$ contacts are reported to produce cells with PCE over 12% (Paudel et al (2011) $^{108}$), when Cu is also used.

Arsenic telluride (As$_2$Te$_3$) is a narrow gap semiconductor with two crystal phases, monoclinic (most stable at ambient pressure) and rhombohedral. Although not as well studied as a back contact material for CdTe as is Sb$_2$Te$_3$, As$_2$Te$_3$ is likely to dope the interface region of the CdTe with arsenic. Al Turkestani’s As$_2$Te$_3$ contacts outperformed his equivalent Sb$_2$Te$_3$ contacts (PCE 3.6%). Romeo et al (2010) $^{110}$ reported 15.8% PCE with As$_2$Te$_3$/Cu contacts—both deposited at 200°C, in this case outperforming Sb$_2$Te$_3$ contacts. Romeo et al (2017) $^{111}$ have had higher PCE, finding very similar results (15%-16%, FF 70%-72%) with As$_2$Te$_3$, Bi$_2$Te$_3$, and ZnTe and slightly reduced PCE with Sb$_2$Te$_3$. It is presumed that the toxicity of arsenic has sometimes driven the preferential choice of Sb$_2$Te$_3$ over As$_2$Te$_3$. When CdTe is heavily doped with arsenic, there is a possibility that some As$_2$Te$_3$ is formed at the rear surface. $^{104}

Bismuth telluride is a narrow gap semiconductor, with rhombohedral crystal symmetry, that can be doped n-type or p-type. Bismuth is a reasonably cheap and relatively non-toxic element. Lee and Myers (2015) $^{112}$ measured a valence band offset of 0.22 eV for the Bi$_2$Te$_3$/CdTe (111) interface. Romeo et al (2013) $^{113}$ used Bi$_2$Te$_3$ as a back contact material achieving 10.2% PCE ($V_{oc}$ 775 mV, $J_{sc}$ 22.9 mA cm$^{-2}$, and FF 57.5%). Tang et al (2014) $^{114}$ reported similar PCE and FF values, with a lower $V_{oc}$. Romeo et al (2017) $^{111}$ claim that there is little difference in performance between using Bi$_2$Te$_3$ and As$_2$Te$_3$. It would be interesting to see whether Bi$_2$Te$_3$ could be used on in situ p-type doped CdTe where any low-level n-type doping effect from Bi is unlikely to cause compensation.

5 | SELENIDE BACK CONTACTS

Selenides are often chemically like their sulfide counterparts. Many metals form stable selenides. Some of these have a two-dimensional layered structure. The only uses of binary
metal selenides as back contacts to CdTe-based solar cells known to the authors are TiSe₂ and VSe₂. The promising work function value reported by Kraft et al (TSF 2003) for VSe₂ did not produce Ohmic contacts when CdTe was deposited on these selenides. This was attributed to the formation of dipoles at the VSe₂ to CdTe interface with an excess of Cd present, due to a higher sticking coefficient of Cd.

Zhao (2008) (University of South Florida) attempted to selenize titanium deposited on the back of a CdTe solar cell. However, the high temperatures required for selenization (>420°C) led to deterioration of the CdTe. Later, Ferekides and Morel (2011) reported four candidate metal selenides: TiSe₂, VSe₂, NbSe₂, and TaSe₂ (no experimental work). Deposition of TiSe₂ onto CdTe by selenization of titanium required too high a processing temperature resulting in some CdTe sublimation.

Copper selenide would be a logical compound to try as a back contact, considering the other binary copper chalcogenides Cu₂Te and CuS reported. One reason for little work on these contacts might be that no good solar cell efficiencies have been achieved to date. The copper-selenium phase diagram is complex, and several Cu-Se compounds exist.

No publications have been found on CdTe solar cells either with NbSe₂ or TaSe₂ contacts. However, attempts have been made to grow CdTe on NbSe₂ substrates. Depositing NbSe₂ onto CdTe led to similar dipole formation issues as was reported for VSe₂ on CdTe. Gao et al (2014) deposited VSe₂ by electron beam evaporation onto CdTe device structures with a copper-free process. The measured J-V curves had a high series resistance but did show an improvement over devices without the VSe₂ layer (with VSe₂: V oc 716 mV, J sc 20.65 mA cm⁻², FF 60.5%, and PCE 8.95%).

A possible problem with some transition metal chalcogenide contacts is the existence, in many cases, of multiple phases, often of different stoichiometry. One example is titanium selenide, for which several compounds are reported: Ti₅Se₂, Ti₁₁Se₄ and those listed in Murray (1986).

Studies of a set of a single-metal sulfide, metal selenide, and metal telluride counterparts would be interesting. In the case of selenides, any significant diffusion of Se into CdTe would lead to a reduction in bandgap which might change recombination rates at the rear interface. Selenide back contact solar cell results from the literature are summarized (along with sulfide back contacts) in Table 5. There are no reports of MoSe₂ back contacts known to the authors.

### TABLE 4
Selected solar cell J-V parameters from CdTe solar cells with Group IV telluride (SnTe, PbTe) and Group V telluride (As₂Te₃, Sb₂Te₃, and Bi₂Te₃) back contacts reported in the literature

| Reference                        | Contact          | V oc (mV) | J sc (mA cm⁻²) | FF (%) | PCE (%) |
|----------------------------------|------------------|----------|----------------|--------|---------|
| Weng et al (2018)                | ZnTe/Cu/SnTe/metal | 841      | 24.7           | 70.2   | 14.6    |
| Shu et al (2019)                 | SnTe/Ni          | 782      | 24.6           | 68     | 13.1    |
| Swartz et al (2019)              | SnTe:Ti/Au       | Unstated | Unstated       | Unstated | 13.5    |
| Swartz et al (2019)              | PbTe:Ti          | <700     | Unstated       | “Shunted” | 9      |
| Romeo et al (1999)               | Sb₂Te₃          | 858      | 23            | 74     | 14.6    |
| Hodges (2009)                    | Sb₂Te₃          | 820      | 21.3          | 70.0   | 12.2    |
| Hu et al (2011)                  | Sb₂Te₃          | 816      | 25.8          | 62.3   | 13.1    |
| Emziane et al (2005)             | Sb₂Te₃/Mo       | 812      | 25            | 69     | 14      |
| Paudel et al (2011)              | Sb₂Te₃/Cu/Au     | 778      | 22.1          | 71.8   | 12.3    |
| Paudel et al (2011)              | Sb₂Te₃/Au       | 717      | 22.2          | 63.2   | 10.1    |
| Al Turkestani (2009)             | As₂Te₃          | ~600     | 21.6          | 41.5   | 5.4     |
| Romeo et al (2010)               | As₂Te₃/Cu       | 862      | 25.5          | 72     | 15.8    |
| Romeo et al (2013)               | Bi₂Te₃          | 775      | 22.9          | 57.5   | 10.2    |
| Tang et al (2014)                | Bi₂Te₃/Ni       | 650      | 26.9          | 60.7   | 10.6    |

### 6 | SULFIDE BACK CONTACTS

The following metal sulfides are noted as having been used as CdTe back contact materials: CuS, CuInS₂, CuInS₂:N, CuS/ZnS, FeS₂, (Fe,Ni)S₂ and MoS₂. Other sulfur-containing materials are found listed under other categories (eg, BaCuSF under halides). Sulfide back contact solar cell results from the literature are summarized (with selenide back contacts) in Table 5. The as-deposited films were not stoichiometric and required a thermal anneal at 200°C which changed the Cu/S ratio from ~0.75 to 0.95-1.05. Lei et al (2013) obtained 12.2% (V oc 820 mV, J sc 21.6 mA cm⁻², and FF 68.9%) using a 7 nm thick CBD-grown Cu₃S film. Türck et al (2015) obtained 13% PCE (V oc “almost 800 mV,” J sc ~ 24 mA cm⁻², FF ~ 70%)
after annealing at 225°C. Subedi et al (2017)\textsuperscript{127} reported PCE 13% ($V_{oc}$ 806 mV, $J_{sc}$ 22.1 mA cm$^{-2}$, and FF 73%) using (Cu$_{0.05}$Ni$_{0.95}$S)$_2$/Cu/Au back contacts. With copper-containing back contacts, the effect of the back contact is difficult to separate from CdTe doping effects. Woods-Robinson et al.\textsuperscript{128} used a Cu$_{0.60}$Zn$_{0.40}$S back contact to achieve 13.8% PCE ($V_{oc}$ 836 mV, $J_{sc}$ 24.6 mA cm$^{-2}$, and FF 74.4%) using a process that gave 14.0% PCE with a ZnTe:Cu back contact.

Iron sulfide (iron pyrite, FeS$_2$) could be used as a potential back contact in a “Cu-free” process, but iron diffusion into CdTe must be considered. FeS$_2$ nanocrystals, deposited by drop-casting of nanocrystals in a chloroform solution, have been used (Bhandari et al (2015))\textsuperscript{129-132} as a back contact material. They also compared performance with and without the use of copper. With Cu, a PCE of 13.3% ($V_{oc}$ 810 mV, $J_{sc}$ 21.4 mA cm$^{-2}$, FF 72.8%, series resistance 3.1 Ω cm$^2$) was achieved. Without Cu, a PCE of 12.5% was achieved. As the energy gap of FeS$_2$ is only 0.95 eV, it will absorb light itself potentially increasing $J_{sc}$ because it is a p-type conductor (not forming an opposing diode). However, the conductivity is low so too thick a layer will add series resistance. (Cu,Fe)S$_2$ tried by Bastola et al (2018)\textsuperscript{133} gave 12% PCE.

Nickel alloyed iron sulfide was used by Bastola et al (2017).\textsuperscript{134} Ni$_{0.8}$Fe$_{1.2}$S$_2$ was observed to be p-type with up to 10% Ni, but n-type for 20% or greater Ni content. As Ni content increased from 0% to 30%, $V_{oc}$ increased monotonically from 834 to 848 mV, while $J_{sc}$ decreased monotonically (rapidly above 20% Ni). FF reached a maximum at 5% Ni, as did efficiency (PCE 11.8%, $V_{oc}$ 835 mV, $J_{sc}$ 19.7 mA cm$^{-2}$, and FF 70.8%). The Ni$_{0.1}$Fe$_{0.9}$S$_2$/Au contact was a small (8% relative) improvement on their standard Cu/Au contact.

Nickel sulfide has been tried as a hole transport layer in perovskites\textsuperscript{135} (Ni$_3$S composite with carbon gave low-performance perovskite solar cells with PCE ~5%, $V_{oc}$ < 600 mV, FF < 40%), but no reports have been found using Ni$_3$S in CdTe solar cells.

Barium copper sulfide (BaCu$_4$S$_3$ or BCS) has been used by Subedi et al (2019)\textsuperscript{136} in a recent bifacial solar cell study, in which ITO was deposited on top of ~100 nm of BCS on 3 µm of CdTe. Front-side (through glass) illumination gave PCE 12.3% ($V_{oc}$ 823 mV, $J_{sc}$ 21.2 mA cm$^{-2}$, FF 70.4%, and $R_s$ 3.8 Ω cm$^2$), but only a PCE of 1% when rear illuminated ($J_{sc}$ 2.8 mA cm$^{-2}$).

In the substrate configuration, X. Tan (2017)\textsuperscript{137} at the University of Toledo has studied CIS and nitrogen-doped CIS as back contacts in glass/Mo/CIS/CdTe/CdS solar cells. The best PCE was only 3.84% in a variant structure (glass/Mo/MoO$_3$/CIS:N/CdTe/CdS).

Molybdenum sulfide (MoS$_2$) was used as a back contact material by Yuan et al (2017).\textsuperscript{138} A study of different thicknesses of MoS$_2$ gave a maximum PCE of 13.7%. The estimated valence band offset between CdTe and MoS$_2$ was 0.56 eV, whereas Deng et al (2020)\textsuperscript{139} estimated 0.46 eV. The contact metal used by Yuan et al was gold (good work function match to MoS$_2$); nickel would have been an interesting comparison. It is noted that making Ohmic contacts to MoS$_2$ is itself not trivial.\textsuperscript{140}

### 7 Metal Oxide Back Contacts

Oxides are often used as transparent conducting front contact materials (eg, SnO$_2$:In (ITO), SnO$_2$:F (FTO), ZnO:Al (AZO)). Bandgap values are mostly larger than their sulfide, selenide, and telluride counterparts. As the properties of individual oxides vary considerably, it is better to discuss each oxide separately. However, an attempt is made to group 3d transition metal oxides, where there are some similarities such as the possibility of mixed valency of the metal in the case of molybdenum and vanadium oxides. Diffusion of 3d metal ions into CdTe must be considered, especially for those cases in which deep levels are formed which can in some cases dramatically decrease minority carrier lifetime.

The question of what role the oxygen plays at CdTe surfaces, interfaces, and grain boundaries is interesting. Air or oxygen anneals before metallization have been found to improve device performance in arsenic-doped CdTe\textsuperscript{141} and some Cu-doped processes. Major (2016)\textsuperscript{142} discussed the effect of oxygen on grain boundaries largely, but not completely, from the point of view of oxygen exposure during CdTe growth or the CdCl$_2$ activation process.

#### 7.1 Zinc oxide

Zinc (II) oxide (ZnO) is a wide-gap semiconductor with a wurtzite crystal structure and an ambient temperature bandgap of around 3.3 eV. ZnO heavily doped with aluminum (AZO) is a well-known transparent conducting oxide (TCO), and has been used both as a front contact,\textsuperscript{143} and as a back contact material (Parikh (2007),\textsuperscript{144} Heisler et al (2013)\textsuperscript{145}) for CdTe absorber solar cells. Aluminum doping greatly increases the conductivity of ZnO and introduces a Moss-Burstein shift of the bandgap to higher photon energy.

Parikh,\textsuperscript{144} using a thin 80 nm thickness of ZnO:Al obtained 1.79% PCE with no copper, and 5.74% PCE ($V_{oc}$ 475 mV, $J_{sc}$ 22.9 mA cm$^{-2}$, and FF 52.7%) with the use of copper before ZnO:Al deposition (and a short 150°C anneal). Heisler et al (2013)\textsuperscript{145} used RF sputtered ZnO:Al back contacts with both 0.7 and 1.7 µm thick CdTe absorbers, obtaining a maximum PCE of 8.6% (best cell: $V_{oc}$ 744 mV, $J_{sc}$ 19.4 mA cm$^{-2}$, and FF 60%) for the thicker CdTe.

Duenow et al (2009)\textsuperscript{146} published data on composite ZnTe:Cu/ZnO:Al back contacted CdTe cells (also ZnTe:Cu/...
ITO back contacts), obtaining 10.2% PCE ($V_{oc}$ 798 mV, $J_{sc}$ 20.7 mA cm$^{-2}$, and FF 61.7%).

7.2 | Indium oxides

Indium-doped tin oxide (ITO), a highly conductive n-type TCO, has been used as a back contact material. The use of ITO as a back contact interface material is not intuitive as ITO/CdTe junctions have been used as solar cells diode junctions.

Calnan (2008)\textsuperscript{147} looked at the optical transmission of indium-doped metal oxides for front and back contacts to CdTe absorber cells,\textsuperscript{148} but did not publish any CdTe absorber solar cell PCE data.

Romeo et al. (2007)\textsuperscript{149} obtained 10% PCE with a Cu/ITO back contact, 18nm a cell which was bifacial. Using nanocrystal CdTe in an ink, Crisp et al (2014)\textsuperscript{150} obtained PCE 11.3% ($V_{oc}$ 686 mV, $J_{sc}$ 25.5 mA cm$^{-2}$, FF 64.7%) with a ZnO/CdTe/ITO device in which the n-p junction was between the ZnO and CdTe and ITO formed the back contact.

Swartz et al (2019)\textsuperscript{99} using an ITO/Au back contact on a CdTe nanoparticle treated CdTe absorber obtained PCE 14.7% with other J-V parameters not explicitly stated.

7.3 | Molybdenum oxide

Molybdenum (VI) oxide (MoO$_3-x$) is a wide bandgap semiconductor,\textsuperscript{151} which when perfectly stoichiometric, has a layered structure. As oxygen is lost from MoO$_3$, the bandgap narrows, the material increases in conductivity, and the material structure becomes more complex. Metallic molybdenum (IV) oxide (MoO$_2$) can be formed from MoO$_3$ in reducing conditions.\textsuperscript{152,153}

Table 6 lists several of the papers to publish results using MoO$_{3-x}$ as a back contact for CdTe absorber solar cells. Most of these results are on superstrate configuration cells, except where noted below. It can be seen from Table 6 that several different metals have been used on top of the MoO$_x$, this additional step adds a further complexity to the back contact and reduces the ability to directly compare results from the different groups. The top PCE reported for a MoO$_x$ back contact is 14.6% for a process which includes the use of copper\textsuperscript{154} and 14.1% for a process which excludes copper.\textsuperscript{155}

H. Lin (2012)\textsuperscript{156} observed some Mo$^{5+}$ formation when sputtering, but not when thermally evaporating molybdenum oxide. The minimum series resistance obtained was 4.7 Ω cm$^2$ with 40 nm of evaporated MoO$_3$-$x$ and nickel metallization. An advantage of the MoO$_{3-x}$ layer is that several low-cost metals (including aluminum) can be used on the MoO$_3$-$x$ surface; expensive, high work function metals are not necessary. However, the highest $V_{oc}$ achieved by any researchers found in this analysis was using a gold metallization.\textsuperscript{157} Lin et al\textsuperscript{155} showed greater PCE stability of CdTe devices when using Ni or Mo metallization on MoO$_3$ at the back contact compared to the less stable Cr and Mg metals, and a very unstable Al contact. The stability tests used were a 19 hours anneal at 200°C and a 400 day light-soak.

Paudel and Yan (2014)\textsuperscript{158} performed x-ray photoelectron spectroscopy measurements on the CdTe to MoO$_3$ interface finding a $2.75 \pm 0.2$ eV valence band offset (barrier to holes). Their FF decreased with increasing MoO$_3$ thickness from 2 nm.
to 40 nm (series resistance increased). An increase in $V_{oc}$ by 50 mV was observed when a 2 nm thick MoO$_3$ layer was used.

Gretener (2015), using substrate configuration cells, concluded that MoO$_2$ was present at the CdTe interface in the highest performing cells. MoO$_2$ is expected to have a higher work function and more metallic conduction than MoO$_3$. Drayton (2015) also found that low-temperature deposition MoO$_x$ deposition gave MoO$_2$ XPS peak positions.

Ta$_2$O$_5$ has been successfully used as a high resistance layer between CdS and CdTe (increasing $V_{oc}$ and FF), but no results have been found using Ta$_2$O$_5$ as a back contact interfacial layer.

### 7.4 3d transition metal oxides

Vanadium oxide and nickel oxide have been used as CdTe absorber solar cell back contact materials. Transition metals from the 3d series often form deep levels within semiconductors. If CdTe carrier lifetime is reduced by the 3d transition metal, and there is a mechanism for diffusion, then that metal oxide is probably best avoided.

Vanadium can form the following oxides: V$_2$O$_3$, VO$_2$, and V$_2$O$_5$. The bandgaps of the vanadium (III) and vanadium (IV) oxides are narrow, only the vanadium (V) oxide bandgap is wide enough to be useful as a front contact, or as a back contact with high transmission in the visible or NIR. Deposited V$_2$O$_5$ films can have a range of bandgaps from 2.25 to 3.1 eV. V$_2$O$_5$ is thermochromic that its color (bandgap) changes rapidly (decreases) with increasing temperature. Vanadium doping of CdTe can produce associated deep levels and is used to produce very resistive CdTe.

Paudel et al (2015) looked at three transition metal oxides (MoO$_{5-x}$, V$_2$O$_{5-x}$, and WO$_{3-x}$) with a view to making copper-free back contacts. Within these three systems, the best PCE was using molybdenum oxide (14.1% PCE, $V_{oc}$ 815 mV, $J_{sc}$ 25.1 mA cm$^{-2}$, FF 67.9%, and $R_s$ 6.4 Ω cm$^2$), whereas the vanadium oxide cells gave 13.6% ($V_{oc}$ 778 mV, $J_{sc}$ 25.1 mA cm$^{-2}$, FF 69.4%, and $R_s$ 6.2 Ω cm$^2$), and the tungsten oxide 12.9% ($V_{oc}$ 767 mV, $J_{sc}$ 24.6 mA cm$^{-2}$, FF 66.7%, and $R_s$ 6.5 Ω cm$^2$).

Shen et al (2016) obtained 10.4% PCE ($V_{oc}$ 729 mV, $J_{sc}$ 24.7 mA cm$^{-2}$, and FF 57.6%) using gold contacts to V$_2$O$_5$ back contacts. These results were further improved using a thin (2 nm) Cu layer before the V$_2$O$_5$ deposition leading to 13.7% PCE ($V_{oc}$ 797 mV, $J_{sc}$ 24.8 mA cm$^{-2}$, and FF 69.4%), very similar to Paudel el. (2015). On timescales of up to a year, some PCE degradation was observed due to a small increase in series resistance.

Nickel (II) oxide (NiO), a p-type semiconductor, was used as a CdTe back contact by Ishikawa et al (2016) and Xiao et al (2017). Ishikawa et al used sputtered Ag-doped NiO back contacts. PCE with NiO:Ag was 5.14% ($V_{oc}$ 598 mV, $J_{sc}$ 16.4 mA cm$^{-2}$, and FF 53%), compared to a baseline carbon-based contact giving PCE 15.3%. In the work of Xiao et al PCE was maximized at 20 nm NiO thickness and further improved with a 3 nm thick layer of copper deposited before.

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**Table 6** List of J-V characteristics from solar cells using molybdenum oxide in the back contact process, references and whether copper is used in the process

| Reference                  | Device structure or contact | $V_{oc}$ (mV) | $J_{sc}$ (mA cm$^{-2}$) | FF (%) | PCE (%) | Process contains copper |
|----------------------------|-----------------------------|---------------|-------------------------|--------|---------|------------------------|
| Yang et al (2016)          | CdTe/Cu/MoO$_x$/Cu-Au       | 799           | 25.3                    | 70.1   | 14.2    | Yes                    |
| Zhang et al (2018)         | CdTe/MoO$_x$/Cu             | 830           | 24.2                    | 72.7   | 14.6    | Yes                    |
| Wang et al (2018)          | CdTe/MoO$_x$/Mo             | 794           | 24.9                    | 69.0   | 13.7    | Yes                    |
| Hao Lin et al (2012)       | CdTe/MoO$_x$/Ni             | 808           | 22.0                    | 72.6   | 12.9    | No                     |
| Hao Lin et al (2012)       | CdTe/MoO$_x$/Al (superstrate) | 815           | 22.3                    | 68.4   | 12.4    | No                     |
| Drayton et al (2015)       | Cu/MoO$_x$/Ni               | 792           | 21.9                    | 68.3   | 11.9    | Yes                    |
| Paudel et al (2015)        | MoO$_x$/Au                  | 815           | 25.4                    | 67.9   | 14.1    | No                     |
| Paudel et al (2015)        | MoO$_x$/Au                  | 790           | 22.6                    | 65.0   | 11.6    | No                     |
| Paudel et al (2013)        | Te/MoO$_x$/Cu               | 833           | 22.4                    | 71.4   | 13.3    | Yes                    |
| Perrenoud (2012)           | CdTe/MoO$_x$                | 329           | 16.4                    | 38.5   | 2.1     | No                     |
| Irfan et al (2012)         | MoO$_x$/Ni                  | 807           | 20.7                    | 70.8   | 11.8    | Uncertain              |
| Perrenoud (2012)           | Cu/Te/MoO$_x$               | 768           | 21.4                    | 68.6   | 11.3    | Yes                    |
| Gretener (2015)            | MoO$_x$/Te/CdTe (substrate) | 733           | 22.0                    | 62.3   | 10.0    | Yes                    |
| Gretener (2015)            | MoO$_x$/CdTe                | 597           | 20.3                    | 48.4   | 5.9     | Yes                    |
| Dang and Singh (2015)      | Substrate/NW CdS/CdTe/MoO$_x$/Au | 752           | 25.6                    | 57.1   | 11.0    | No                     |
| Artegiani (2019)           | CdTe/MoO$_x$/Au             | 852           | 19.4                    | 61.6   | 10.2    | Yes                    |
the NiO. Maximum PCE with the Cu layer was 13.5% (\(V_{oc}\) 791 mV, \(J_{sc}\) 23.7 mA cm\(^{-2}\), FF 68.9\%, and \(R_s\) 9.5 \(\Omega\) cm\(^{-2}\)); without Cu, the maximum PCE was 12.2\% (rollover in forward bias). Degradation in PCE at 80°C was reduced with 20 nm NiO in the back contact.

Alloying nickel oxide with cobalt\(^{167}\) (Ni\(_{1-x}\)Co\(_x\)O\(_2\)) is a possibility for fine tuning of the material’s electron affinity (probably at the expense of conductivity).

Titanium dioxide (TiO\(_2\)) is widely used as an electrode material in organic solar cells. However, it has not been tried (to the authors’ knowledge) as a CdTe solar cell back contact material probably due to its expected high valence band offset (2.6 eV\(^{168}\)). TiO\(_2\) has been used as an n-type buffer layer\(^{169}\) for p-CdTe absorber solar cells. Titanium metal has been used as a back contact (NREL 2009).\(^{146}\) Oxide formation over time could lead to a possible TiO\(_2\) intermediate layer. Long-term diffusion of Ti into CdTe might reduce doping levels due to deep level formation.\(^{170}\)

No other 3d transition metal oxides are known to have been used as CdTe absorber solar cell back contact materials.

### 7.5 Aluminum oxide

Very thin layers of aluminum oxide (Al\(_2\)O\(_3\)) have been suggested as passivation layers for the rear surface of CdTe. Al\(_2\)O\(_3\) has a very large bandgap and is typically very insulating. An Al\(_2\)O\(_3\) barrier must be very thin to enable electrons to tunnel through. For very thin layers, there is the issue of uniformity, do areas exist with missing Al\(_2\)O\(_3\) or thicker regions exist where tunneling is inhibited? This is a difficult characterization issue at a buried interface that is also typically very rough.

The motivation for this approach is that minority carrier lifetimes have been observed to increase in some semiconductor systems when Al\(_2\)O\(_3\) is applied to the surface (eg, HgCdTe,\(^{171}\) Si,\(^{172}\) and CIGS\(^{173}\)). However, in a solar cell, the interface must pass current and impressive increases in lifetime in Al\(_2\)O\(_3\) passivated CdTe\(^{174}\) have not been developed into cells with excellent PCE.

There is also the question of whether copper is used in the process, so the interface in some studies can be to other materials (eg, CdTe/Cu\(_x\)Te/Al\(_2\)O\(_3\)).\(^{175}\) rather than directly depositing Al\(_2\)O\(_3\) onto CdTe.

Atomic layer deposited (ALD) Al\(_2\)O\(_3\) on TEC\(^{™}\) 10 substrates has also been used to overcome shorts due to pinholes in CdTe solar cells (TEC\(^{™}\) 10/Al\(_2\)O\(_3\)/CdS/CdTe/ZnTe/CdS:Ni).\(^{176}\) Liang et al (2015)\(^{177}\) obtained PCE 12.1\% using 1 nm thick ALD Al\(_2\)O\(_3\). Lin et al (2016)\(^{178}\) achieved PCE of 13.0\% (\(V_{oc}\) 782 mV, \(J_{sc}\) 24.2 mA cm\(^{-2}\), and FF 68\%) with a 9 nm Cu back contact layer followed by a 2 nm ALD-Al\(_2\)O\(_3\) layer. Munshi et al (2018)\(^{179}\) achieved PCE 16.5\% (\(V_{oc}\) 827 mV, \(J_{sc}\) 28.1 mA cm\(^{-2}\), and FF 71.1\%) with a thin 0.5 nm Al\(_2\)O\(_3\) layer, but this was with dual Cd(Se,Te)/CdTe absorber layers which gave slightly higher \(V_{oc}\) and FF (same \(J_{sc}\)) without the Al\(_2\)O\(_3\) layer.

### 7.6 Copper oxide

There are three stoichiometric copper oxide compounds (Cu\(_2\)O, CuO, and Cu\(_3\)O\(_4\)).\(^{180}\) Copper (I) oxide (CuO) is a p-type semiconductor with a bandgap of \(-2.1\) eV. The contact resistance of CuO on p-type CdTe was measured by Ghosh et al (2002).\(^{181}\) The contact resistance measurement of \(2.2 \times 10^{-2} \Omega \text{cm}^2\) appeared favorable compared to similar measurements the authors performed on Ni-P/Au, Cu/Au, or Sn/Bu contacts. Türck et al (2016)\(^{182}\) obtained PCE 15.2\% (\(V_{oc}\) 832 mV, \(J_{sc}\) 25.0 mA cm\(^{-2}\), and FF 73.1\%) on a CdTe absorber cell on TEC\(^{™}\) 15M substrate with CdS:O buffer and a Cu\(_3\)O/Au back contact. Heat treatment was required after Cu\(_2\)O deposition to achieve high PCE. Masood et al (2017)\(^{183}\) at the University of Science and Technology of China, Hefei estimated the barrier height at the CuO/CdTe interface to be around 0.35-0.44 eV. Their best PCE was 12.2\% (\(V_{oc}\) 753mV, \(J_{sc}\) 26.7 mA cm\(^{-2}\), and FF 60.2\%) with 10 nm CuO deposited before gold metallization. CuO has also been used as a HTM in perovskite solar cells,\(^{184}\) and its electronic properties compared with other copper compounds.\(^{15}\)

### 7.7 Oxide back contacts compared

Table 7 shows a comparison of the highest PCE CdTe absorber solar cells found in the literature using different oxide back contact materials. The maximum \(V_{oc}\) with an oxide back contact is about 830 mV—this is 20-40 mV below the maximum \(V_{oc}\) routinely achieved in several laboratories in recent years. \(J_{sc}\) is more difficult to compare between different laboratories, but with five reports of oxide materials greater than 24 mA cm\(^{-2}\) some oxides can certainly pass significant current at zero bias. No FF above 73.1\% has been achieved with an oxide back contact.

It would be interesting to see more oxide materials applied to graded Cd(Se,Te) absorber solar cells.

### 8 METAL PNICTIDE BACK CONTACTS

Metal pnictides have been little used as back contacts. Two examples of CdTe back contacts using single-metal nitrides have been found: ZrN (PCE 1.68\% in 2014\(^{185}\)) and MoN\(_x\) (Guntur (2011\(^{186}\)), Drayton et al (2015)\(^{159}\) (PCE 5.24\%). A more recent article (Kindvall et al (2017)\(^{187}\)) on the use of MoN\(_x\) (and MoO\(_x\)) on substrate configuration cells did not
explicitly state PCE values but did contain numerous J-V parameters presented in graphic form. When a thick MoN film was used as a back contact, the J-V curves appeared very similar (PCE 12.3%, $V_{oc}$ ~ 780-800 mV, $J_{sc}$ ~ 23 mA cm$^{-2}$, FF ~ 70%, estimated from graphs) to their control device (Te then Ni based paint).

ZrN has been used as a CIGS back contact$^{188}$—optically reflective but with increased series resistance and interface recombination. MoN has been used as a diffusion barrier in CIGS solar cells.$^{189}$

Nickel phosphide was considered as a back contact material.$^{190}$ In this case, Ni$_2$P powder was mixed with the graphite paste applied to the back contact.

The use of pnictides within CdTe absorber solar cell back contact structures is not particularly mature, and no advantage over more established back contact technologies has yet been achieved.

9 | INORGANIC BACK CONTACTS CONTAINING HALIDES

Some complex fluorides have been suggested as p-type transparent contact materials.$^{191}$ Spies (2007)$^{192}$ at Oregon State University examined the use of barium copper tellurium fluoride (BCTF, bandgap 2.3 eV, hole concentration of $10^{20}$-$10^{21}$ cm$^{-3}$, mobility 1-5 cm$^2$ V$^{-1}$ s$^{-1}$) as a CdTe absorber solar cell back contact. A PCE of 1.2% was obtained ($V_{oc}$ 540 mV, $J_{sc}$ 4.8 mA cm$^{-2}$, and FF 46%).

A collaboration in Japan between Ryukoku University and the Kisarazu National College of Technology, Chiba, has studied PLD quaternary chalcogenide fluoride materials for back contacts. Their first paper (2014) used the selenide-fluoride BaCuSeF.$^{193}$ A PCE of 2.82% ($V_{oc}$ 796 mV, $J_{sc}$ 6.0 mA cm$^{-2}$, and FF 59%) was obtained, which increased to 3.18% ($V_{oc}$ 714 mV, $J_{sc}$ 9.21 mA cm$^{-2}$, and FF 41%) with the inclusion of a thin Ni$_{0.97}$Li$_{0.03}$O interlayer. PCE was improved with a bromine-based back-surface treatment$^{194}$ (PCE 9.91%, $V_{oc}$ 805 mV, $J_{sc}$ 22.1 mA cm$^{-2}$, and FF 55.7%). It is noted that a Cu$_x$Te layer formed during processing with x ~ 1.4. Using strontium instead of barium and improving back-surface conductance by using ITO on top of the fluoride layer$^{195}$ improved the PCE to 14.3% ($V_{oc}$ 804 mV, $J_{sc}$ 27.5 mA cm$^{-2}$—very high if reproducible, FF 65%). The optimum thickness of SrCuSeF was 34 nm (with 200 nm of ITO on top). The authors believe that the low conductivity of the fluoride layer is limiting series resistance and hence FF. Doping with sodium$^{196}$ gave a small improvement in FF raising the PCE to 14.7% ($V_{oc}$ 806 mV, $J_{sc}$ 27.5 mA cm$^{-2}$, and FF 66.1%). Substituting sulfur for selenium (BaCuSF),$^{197}$ again used with ITO on top (platinum metallization), gave PCE 13.9% ($V_{oc}$ 818 mV, $J_{sc}$ 25.2 mA cm$^{-2}$, and FF 67.5%).

The use of quaternary inorganic materials allows a huge range of potential materials to be considered. However, controlling the composition of many quaternary materials can often be difficult compared to ternary or binary materials, as well as allowing a large range of potential native defects.

Perovskite halide back contacts to CdTe devices have been studied by the University of Toledo group.$^{198,199}$ Small performance gains (4-9 mV in $V_{oc}$, 1.4%-2.1% in absolute FF) were achieved over their standard Cu/Au back contacts. Some devices gave $V_{oc}$ 870 mV which the authors said they would investigate further. The authors also have used the reaction of methylammonium iodide (MAI) with cadmium (forming (CH$_3$NH$_3$)$_2$CdI$_4$ (or MA$_2$CdI$_4$) perovskite in solution) to selectively remove Cd from the back surface, leaving the surface Te-rich. Either copper/gold or ITO contacts (transparent) were then applied. MAI treated CdTe with Cu/Au (0.5 nm Cu) contacts achieved 13.0% average PCE ($V_{oc}$ 824 mV, $J_{sc}$ 20.5 mA cm$^{-2}$, and FF 77.1%) and 13.5% in the champion cell. MAI treated CdTe with Cu/ITO back contacts achieved PCE 12.2% ($V_{oc}$ 823 mV, $J_{sc}$ 21.4 mA cm$^{-2}$, and FF 69.3%); MAI treated CdTe with Cu-free ITO back contacts gave a champion cell with PCE 10.0% ($V_{oc}$ 748 mV, $J_{sc}$ 21.0 mA cm$^{-2}$, and FF 57.9%). The Cu-free cell therefore had reduced $V_{oc}$ and FF.

### TABLE 7  Comparison of best CdTe absorber solar cell performance with different oxide back contacts

| Reference               | Oxide back contact | $V_{oc}$ of maximum PCE cell (mV) | $J_{sc}$ of maximum PCE cell (mA cm$^{-2}$) | FF of maximum PCE cell (%) | PCE (%)       |
|-------------------------|--------------------|-----------------------------------|-------------------------------------------|---------------------------|---------------|
| Türck et al (2016)$^{182}$ | Cu$_2$O             | 832                               | 25.0                                      | 73.1                       | 15.2          |
| Zhang et al (2018)$^{184}$ | CdTe/MoO$_3$/Cu     | 830                               | 24.2                                      | 82.7                       | 14.6          |
| Shen et al (2016)$^{164}$   | V$_2$O$_5$           | 806                               | 24.8                                      | 70.0                       | 14.0          |
| Paudel et al (2013)$^{250}$ | WO$_{0.9}$          | 787                               | 24.6                                      | 66.7                       | 12.9          |
| Xiao et al (2017)$^{196}$   | Cu/NiO              | 796                               | 24.2                                      | 70.2                       | 13.5          |
| Heisler et al (2013)$^{145}$ | ZnO:Al              | 745                               | 19.3                                      | 64                         | 9.3           |
| Khryponov et al (2019)$^{251}$ | ITO                 | 808                               | 18.7                                      | 69                         | 10.4          |
| Swartz et al (2019)$^{99}$  | ITO/Au              | -                                | -                                         | -                          | 14.7          |
| Wu et al (2006)$^{254}$     | Cu$_3$Te/ITO        | 806                               | 25.0                                      | 69.2                       | 13.7          |
Copper (I) iodide has been used as a back contact material (Li et al. (2019)\textsuperscript{205}). PCE was maximized with a very thin (5 nm) CuI layer (PCE 14.5%, $V_{oc}$ 795 mV, $J_{sc}$ 25.4 mA cm$^{-2}$, FF 71.9%, and $R_s$ 3.6 Ω cm$^2$). CuI has also been used as a perovskite HTM.\textsuperscript{15} Copper (II) chloride has been used by Artegiani et al. (2019).\textsuperscript{201} In this case, the copper halide is thought to be acting as a reproducible source for a very small amount of copper (equivalent to 0.1 nm of pure copper) leading to an improvement in device stability after 1000 hours of 80°C stress testing.

Copper is common to all the halide-based back contact technologies listed in Table 8; of the back contact materials in Table 8, only perovskites are potentially compatible with a Cu-free process.

10 | INORGANIC CARBON-BASED BACK CONTACTS

In this section, carbon allotrope back contacts and some materials containing carbon atoms are examined. Several forms of carbon have been used as back contacts, perhaps reflecting the wider research of the time on an allotrope. Graphite is a low-cost material which can be formed easily into a cheap paste, which is often convenient for small laboratories. Such pastes can also be loaded with metal particles, such as copper or silver, or as mentioned earlier HgTe.

The use of graphene with thin film solar cells including CdTe has been reviewed recently (Shi and Jayatissa (2018)\textsuperscript{202}; this included the usage of graphene in the front contact. Cu nanowires combined with graphene were used by Liang et al. (2012)\textsuperscript{203} (PCE 12.1%, $V_{oc}$ 801 mV, $J_{sc}$ 22.4 mA cm$^{-2}$, and FF 67.4%); this could be just a reasonably effective way of delivering restricted amounts of copper to the back surface. Graphene has been studied, doped with boron by Lin et al. (2011)\textsuperscript{204} (PCE 7.86%, $V_{oc}$ 674 mV, $J_{sc}$ 22.0 mA cm$^{-2}$, and FF 55.2%).

Single-Walled carbon nanotubes (SWCNT) have also been used. Barnes et al. (2007)\textsuperscript{205} used SWCNTs as a transparent back contact on top of Cu$_2$Te on CdTe (PCE 12.4%). Khanal’s Cu-free SWCNT device\textsuperscript{206} reached 11.3% PCE ($V_{oc}$ 788 mV, $J_{sc}$ 21.8 mA cm$^{-2}$, and FF 66.5%). Phillips et al. (2013)\textsuperscript{22} reported further work on SWCNT/Au contacts, reporting 11.0 ± 2.8% PCE. Bin Li et al. (2016)\textsuperscript{207} obtained 9.71% PCE ($V_{oc}$ 692 mV, $J_{sc}$ 22.7 mA cm$^{-2}$, and FF 61.9%) after a 320°C annealing step. Alfadhili et al. (2017)\textsuperscript{208} attempted to dope SWCNTs with triethylthoxylamine hexachlororantimonate increasing $V_{oc}$ but adversely impacting FF (best results: PCE 10.6%, $V_{oc}$ 805 mV, $J_{sc}$ 19.4 mA cm$^{-2}$, and FF 68.9%).

The mobility of individual nanotubes is very high, up to 10$^5$ cm$^2$ V$^{-1}$ s$^{-1}$, but the effective sheet resistance remains high compared to good TCOs, at over 500 Ω/sq at a film thickness of 500 nm, due to relatively poor conduction between nanotubes. This is a generic issue with nanowire structures in any material for use as a carrier transport layer in solar cells: both internal conductivity and effective contact conductance need to be high.

Koirala et al. (2014)\textsuperscript{209} studied PECVD grown silicon alloyed with carbon, heavily p-type doped with hydrogen and boron (a-Si$_{1-x}$C$_x$Ge:H) as a CdTe back contact material. The devices had a high series resistance (12 Ω cm$^2$), reducing FF (48.8%) compared to their reference Cu/Au contacts (FF 67%).

Considering carbon containing compounds, Paudel and Yan (2016)\textsuperscript{210} tried copper thiocyanate (CuSCN) back contacts. This was not the first use of CuSCN as a back contact as Tenaza et al. (2005)\textsuperscript{211} used it in a thin absorber solar cell of structure ZnO/CdTe/CuSCN, obtaining very poor preliminary solar cell J-V parameters ($V_{oc}$ ~ 200 mV, $J_{sc}$ < 1 mA cm$^{-2}$, and FF 28%). A high PCE of 13.7% was obtained ($V_{oc}$ 866 mV, $J_{sc}$ 22.9 mA cm$^{-2}$, and FF 69.1%, $R_s$ 6.6 Ω cm$^2$) with a 5 nm thick CuSCN layer. CuSCN, a wide bandgap (3.4-3.9 eV) p-type semiconductor,\textsuperscript{212} has been used successfully as a HTM with perovskites, reportedly improving their thermal stability compared to many organic HTMs,\textsuperscript{213} and acting as a passivating agent for unbonded lead. Similar CdTe solar cell PCE values were obtained by Pressman (2017)\textsuperscript{214} at the University of Liverpool (PCE 13%, $V_{oc}$ 780 mV, and $J_{sc}$ 26 mA cm$^{-2}$). Montgomery et al. (2019)\textsuperscript{215} (University of Alabama) used two different solvents to deposit CuSCN on the back of a CdSe-CdTe solar cell obtaining 17% PCE, using a CdSe buffer the results are not entirely comparable to CdS buffer cells, but the $V_{oc}$ and FF are very good. Forward-bias rollover is suppressed with CuSCN contacts. It is difficult to deconvolve the thiocyanate intermediate layer from copper doping effects. AgSCN has also been used by the Alabama group (Yan et al. (2019)).

Selected experimental solar cell parameter results from the literature for carbon containing inorganic contacts are collected in Table 9.

11 | ORGANIC MATERIALS AS BACK CONTACTS

Organic contacts can provide interlayers on CdTe. Several materials have been tried, mostly HTMs that have been commonly used before in polymer, DSSC, and perovskite solar cells. Thermal stability is important—the melting point and glass transition temperature must be sufficiently high that solar cell fabrication can be completed, and the finalized cell is stable in use. Most of the work in this area is in its infancy, despite work in the late 1990s on the surface chemistry of organic molecules on CdTe (Cohen et al. (1998)).

An early reference found to J-V results on an organic back contact for p-type CdTe solar cells is by Jarkov (2011)\textsuperscript{219} (Tallinn University of Technology). This study used PEDOT:PSS (poly(3,4-ethylenedioxythiophene): poly(styrenesulfonate)) with conductivity enhancing additives, which gave a (Cu-free process) PCE of 3.8% ($V_{oc}$ 610 mV,
Hall et al. (2016) obtained 5.5% (PCE of the reference process was only 6.6%). Later Wang treated CdTe, before Mo contact deposition. Some increase 21.4 mA cm$^{-2}$, and FF 60%).

V further improved performance to PCE 9.1% (Bromine-methanol etching before PEDOT:PSS deposition and FF 48%) with the most highly doped of their samples.

Jarkov et al. (2013) later tried electrodepositing poly-pyrrole-based back contacts: obtaining 10.4% PCE for poly-pyrrole doped with β-naphthalene sulfonate ($V_{oc}$ 739 mV, $J_{sc}$ 20.9 mA cm$^{-2}$, and FF 67.1%). Earlier work by Koll et al. (2011) at the University of Toledo had shown pyrrole surface treatments to leave the surface Te-rich, as well as having a possible pinhole filling role.

Ferekides and Morel (2011) published a summary report of a contract which looked at many back contact technologies, including the effect of several polymer materials used as back-interface materials with Mo metal contacts. The justification for their use was given in terms of surface dipole modification of the metal work function. The summary report gives little detail on materials, methods, or results, and the polymer work was stated to be “for all practical purposes very preliminary.” Polymers derived from the monomers 4-methoxybenzoic acid (p-anisic acid), 4-chlorobenzoic acid, and 4-cyanobenzoic acid were spin-coated onto CdCl$_2$ treated CdTe, before Mo contact deposition. Some increase in $V_{oc}$ was observed but the device technology was not optimized to minimize series resistance. No results for these polymers are included in the organic back contacts summary given in Table 10.

Spiro-OMeTAD (N$_2$N$_2$N$_2$’.N’$’$.N’$’’.N’$’’’.N’’’-octakis (4-methoxyphenyl)-9,9’-spirobi[9H-fluorene]-2,2’,7,7’-tetramine) is another common HTM used in DSSC and perovskite solar cells. Spiro-OMeTAD hole mobility is very low ($\sim 10^{-5}$–$10^{-3}$ cm$^2$ V$^{-1}$ s$^{-1}$), so a higher conductivity material is required on top. Spiro-OMeTAD is commonly doped and oxidized to increase conductivity. A very common dopant contains lithium, which could diffuse into the CdTe and affect the cell stability. Du et al. (2015) saw an improvement in nanocrystal CdTe solar cells when using spiro-OMeTAD as a replacement HTM for MoO$_{3-x}$. Shalvey et al. (2018) saw that Li-doped spiro-OMeTAD reduced forward-bias rollover in CdTe solar cells, but increased ambient temperature series resistance, resulting in no increase in PCE. Research on improving spiro-OMeTAD and similar materials intended as perovskite HTMs could also possibly benefit CdTe solar cells.

P3HT (Poly(3-hexylthiophene-2,5-diyl)) was found by Major et al. (2017) to act as a pinhole blocker and a back contact material. Shunt resistance was significantly improved, giving better yield and reduced FF spread. P3HT/CdTe interface has also been examined in CdTe quantum dots. Abdul-Manaf et al. (2014) used polyaniline as a pinhole blocking layer. Separating out pinhole blocking and back contact interface effects is not trivial, and no study to date has given a comprehensive treatment of this issue.

Doped P3HT, with a similar HOMO level to spiro-OMeTAD, gave similar results to spiro-OMeTAD. However, Shalvey et al. (2018), also tried PFO (Poly(9,9-di-n-octylfluorenyl-2,7-diyl)), which has a much deeper HOMO level, and found a reduced PCE (9.8%), with enhanced forward-bias rollover.

Another way of viewing the use of an organic intermediate layer between the CdTe and the metal back contact is as a method of modifying the metalwork function (de Boer et al. (2005)). Exact metal work functions often depend on crystal face.

Cobalt phthalocyanine (CoPC) contacts were used by Paudel and Yan (2014) achieving 14.3% PCE ($V_{oc}$ 815 mV, $J_{sc}$ 24.2 mA cm$^{-2}$, FF 72.3%, and $R_s$ 2.7 Ω cm$^{-2}$) in a device free of forward-bias rollover. Maximum $V_{oc}$ was found to be for a 10 nm thick CoPC layer. Copper phthalocyanine (CuPc) has been used as a HTM in perovskites (eg, Ke et al. (2015) PCE 14.7%) but only in 2019 (Varadharajaperumal et al. (2019)) was it used as a CdTe solar cell back contact. In a process with a low 1.3% baseline efficiency, a PCE of 2.7% was achieved.

The table below shows J-V parameters for CdTe absorber solar cells with halide and chalcogenide-halide back contact materials taken from the literature:

| Reference                          | Material                        | $V_{oc}$ (mV) | $J_{sc}$ (mA cm$^{-2}$) | FF (%) | PCE (%) |
|-----------------------------------|---------------------------------|---------------|-------------------------|--------|---------|
| Yanagi et al (2007)               | BaCuTeF                         | 540           | 4.8                     | 46     | 1.2     |
| Yamamoto et al (2015)             | BaCuSeF                         | 805           | 22.1                    | 55.7   | 9.9     |
| Miki et al (2018)                 | BaCuSF/ITO                      | 818           | 25.2                    | 67.5   | 13.9    |
| Kitabayashi et al (2017)          | SrCuSeF/ITO                     | 804           | 27.5                    | 65     | 14.3    |
| Wada et al (2018)                 | SrCuSeF-NaIITO                  | 806           | 27.5                    | 66.1   | 14.7    |
| Bhandari et al (2017)             | Cu/MAPb(0.1)I$_3$/Au            | 838           | 19.6                    | 77.2   | 12.7    |
| Bhandari et al (2017)             | Cu/MAPb(0.3)I$_3$/Au            | 836           | 20.2                    | 77.5   | 13.1    |
| Bhandari et al (2017)             | Cu/MAPb(0.5)I$_3$/Au            | 839           | 19.3                    | 77.8   | 12.6    |
| Bhandari et al (2017)             | Cu/MAPb(0.7)I$_3$/Au            | 841           | 20.0                    | 77.1   | 13.0    |
| X. Li et al (2019)                | CuI                             | 795           | 25.4                    | 71.9   | 14.5    |

TABLE 8 J-V parameters for CdTe absorber solar cells with halide and chalcogenide-halide back contact materials taken from the literature.
The performance potential of metal phthalocyanines as back contacts in CdTe has not been fully explored. Phenyl-C61-butyric acid methyl ester (PCBM), which contains a fullerene group, was used by Walkons et al. (2014) as a CdTe back contact layer and gave a low maximum PCE of ~3% ($V_{oc}$, $J_{sc}$, and FF were all poor); a back contact barrier height of 0.6 V was estimated from series resistance vs temperature measurements.

Pentacene was investigated by Perrenoud (2012)—a PCE of 8.8% was obtained with no etching and no copper applied (low $J_{sc}$ is possibly due to poor quality glass/TCO used in this experiment). Undoped pentacene is a p-type semiconductor; derivatives can have high hole mobilities for organic materials (>1 cm² V⁻¹ s⁻¹).

Swartz et al. (2019), in a set of experiments using CdTe nanoparticles as cavity fillers in CSS-grown CdTe absorber devices, tried another proven perovskite hole contact material, spin-coated EH44 (2,7-Di(N,N-dimethoxyphenylamino)-N-(2-ethylhexyl)carbazole), as an interlayer between CdTe and a gold metallization achieving PCE 15%. EH44 is believed to have a glass transition temperature of only 69°C (lower than spiro-OMeTAD) but unencapsulated perovskite stability at 50°C was improved with EH44 compared to spiro-OMeTAD).

Table 10 shows CdTe solar cell performance results with organic materials as back contacts. $V_{oc}$ values above 700 mV are achieved with all materials, raising $V_{oc}$ above 800 mV appears more challenging with organic back contacts. $J_{sc}$ values are often good, vertical transport of carriers through very thin organic layers is good enough. Achieving FF above 70% appears difficult: low mobility values require very thin layers to avoid significant increases in series resistance.

It is beyond the scope of this review to examine the valence band offsets to CdTe for every material in this review.

Table 9. Selected CdTe absorber solar cell results from the literature using carbon containing inorganic back contacts (including carbon allotropes, carbides and thiocyanates)

| Reference | Back contact or device structure | $V_{oc}$ (mV) | $J_{sc}$ (mA cm⁻²) | FF (%) | PCE (%) |
|-----------|---------------------------------|---------------|---------------------|--------|---------|
| Liang et al (2012) | Cu NW/graphene | 801 | 22.4 | 67.4 | 12.1 |
| Lin et al (2011) | B-doped graphene | 674 | 22.0 | 55.2 | 7.86 |
| Alfadhili et al (2017) | Doped SWCNT | 805 | 19.4 | 68.9 | 10.6 |
| Phillips et al (2013) | SWCNT | 773 | 21.2 | 67.2 | 11.0 |
| Khanal (2014) | SWCNT | 779 | 21.8 | 66.5 | 11.3 |
| Koirala et al (2014) | a-Si1-xCbx:H | 713 | 22.1 | 48.8 | 7.7 |
| B. Li et al (2016) | SWCNT/Au | 692 | 22.7 | 61.9 | 9.7 |
| Paudel & Yan (2016) | CdTe/CuSCN/Au | 866 | 22.9 | 69.1 | 13.7 |
| Pressman (2017) | CuSCN | 780 | 26 | ~64 | 13 |
| Montgomery et al (2019) | CdSe/CdTe/CuSCN | 860 | 28.2 | 70.3 | 17.0 |

12 | SUMMARY

The search for an ideal back contact for p-type CdTe solar cells has not yet found a single solution. While back contact quality is not the only limiting factor in CdTe absorber solar cell performance, choosing poor contact materials can limit photovoltaic conversion efficiency or lead to degradation over time.

If the highest efficiency is required, a metallic or near metallic conductivity is necessary. At the same time, the interface must have a low defect density to avoid excessive carrier recombination. An ideal back contact will act as an electron reflector. Carriers need to arrive at the rear contact, so high carrier lifetime within the CdTe is a precondition, as well as a low density of defects at grain boundaries and the rear interface.

Similarities between the CdTe back contact issue and the hole transport layer in perovskite solar cells are noted. The range of organic materials used as HTMs in the extensive but less mature perovskite solar cell literature is already large. Concerns common to CdTe and perovskite solar cells include the thermal stability of the contact material itself, encapsulation, maximizing transport layer conductance, dopant diffusion, and cost of materials. Wide-gap perovskites are often aimed at tandem cell architectures and therefore require high NIR transparency. The following nonexclusive list of inorganic materials has been used as back contacts for both CdTe and perovskite solar cells: MoO₃, NiO, CuOₓ, MoS₂, V₂O₅, NiS, CuSCN, Cul, CuPc, and carbon allotropes. Organic HTMs used on perovskite materials are too numerous to mention here and have been reviewed recently by Urieta et al (2018) and Pitchaiya et al (2020). A small fraction of these organic materials already has been used as CdTe back contacts—a systematic approach to their trial would be useful considering not...
only band alignment but also their long-term stability and compatibility with a metal or other very high conductivity material. The only inorganic perovskite HTMs mentioned by Pitchaiya et al not known to have been used on CdTe are CuCrO$_2$ and CuGaO$_2$.

The ability to dope p-type CdTe using group V elements up to and above the $10^{16}$ cm$^{-3}$ level allows the back contact to be decoupled from the requirement for including copper-containing compounds in the back contact structure: A wider choice of materials is available.

Ultimately, material costs matter, and any expensive materials removed from a process. In terms of impure elements, tellurium cost is expected to be the largest single component of the materials bill of thin film CdTe solar cells. Expensive metals such as gold or platinum are useful in fundamental studies but too costly in production. As tellurium is a moderately rare element itself, a crude guide is that any material used in the CdTe cell should cost significantly less than Te.

Promising materials include thin interlayers of stable materials that will not diffuse out to dope CdTe. Organic layers offer the widest range of tuneability but need to be engineered to be stable at subsequent processing temperatures. Other suggestions for further trial include Bi$_2$Te$_3$ on arsenic-doped CdTe; MoS$_2$/Ni, copper-free thiocyanates and phthalocyanines, and a wider selection of perovskite like halides than has been tried until now.

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REFERENCES

1. Shockley W, Queisser HJ. Detailed balance limit of efficiency of P-n junction solar cells. J Appl Phys. 1961;32(3):510-519. https://doi.org/10.1063/1.1736034
2. Best Research-Cell Efficiency Chart. https://www.nrel.gov/pv/cell-efficiency.html. Accessed Nov 14, 2019
3. Britt J, Ferekides C. Thin-film CdS/CdTe solar cell with 15.8% efficiency. Appl Phys Lett. 1993;62(22):2851-2852. https://doi.org/10.1063/1.109629
4. First Solar Achieves Yet another Cell Conversion Efficiency World Record. https://investor.firstsolar.com/news_press-release-details/2016/First-Solar-Achieves-Yet-Another-Cell-Conversion-Efficiency-World-Record/default.aspx. Accessed Nov 14, 2019
5. Green MA, Dunlop ED, Levi DH, Hohl-Ebinger J, Yoshita M, Ho-Baillie AWY. Solar cell efficiency tables (version 54). Prog Photovolt Res Appl. 2019;27(7):565-575. https://doi.org/10.1002/pip.3171
6. First Solar Series 6 Module. http://www.firstsolar.com/en-EMEA/Modules/Series-6. Accessed Nov 14, 2019
7. Wei S-H, Zhang SB, Zunger A. First-principles calculation of band offsets, optical bowings, and defects in CdS, CdSe, CdTe, and their alloys. J Appl Phys. 2000;87(3):1304-1311. https://doi.org/10.1063/1.372014

| Reference/comments | Organic back contact or interface layer | $V_{oc}$ (mV) | $J_{sc}$ (mA cm$^{-2}$) | FF (%) | PCE (%) | $R_s$ (Ω cm$^2$) |
|--------------------|---------------------------------|-------------|----------------|--------|--------|--------------|
| Swartz et al (2019) | EH44/Au | - | - | - | 15 | |
| Paudel and Yan (2014) | 13 nm CoPc/Au | 815 | 24.3 | 72.3 | 14.3 | 4.9 |
| Major et al (2017) | P3HT [no Cu] | 841 | 25.5 | 66.5 | 14.25 | |
| Major et al (2017) | P3HT [with Cu] | 767 | 22.8 | 65.7 | 11.54 | |
| Walkons et al (2014) | P3HT | 780 | 22.3 | 70.8 | 12.26 | |
| Wang et al (2016) | PCBM/Pt | 700-800 | 21 (at best, estimated) | low | ~3 | ~100 |
| Jarkov et al (2011) | PEDOT:PSS | 610 | 17.8 | 36.0 | 3.8 | - |
| Wang et al (2016) | PEDOT:PSS | 710 | 21.4 | 60 | 9.1 | |
| Jarkov et al (2013) | PEDOT:PSS/C/Ni | 795 | 22 | 72.3 (est.) | 12.65 | |
| Perrenoud (2012) | Pentacene/Au | 753 | 18.1 | 64.6 | 8.8 | |
| Jarkov et al (2013) | Polypyrrole | 757 | 27.1 | 54.0 | 11.25 | - |
| Shalvey et al (2018) | Spiro-OMeTAD | 750 | 22.7 | 59.4 | 11.26 | |
| Shalvey et al (2018) | PFO | 750 | 25.3 | 50 | 9.8 | |

TABLE 10 J-V results from articles reporting organic materials as back contacts to CdTe absorber solar cells
8. Ponpon JP, Siffert P. Barrier heights on cadmium telluride Schottky solar cells. *Rev Phys Appl (Paris)*. 1977;12(2):427-430. https://doi.org/10.1051/rphysap:01977001202042700

9. Wald FV. Applications of CdTe. A review. *Rev Phys Appl (Paris)*. 1977;12(2):277-290. https://doi.org/10.1051/rphysap:019770012020027700

10. Fahrenbruch AL. Ohmic contacts and doping of CdTe. *Solar Cells*. 1987;21(1-4):399-412. https://doi.org/10.1007/BF0379-6878(1987)09138-4

11. Demtsu SH, Sites JR. Effect of back-contact barrier on thin-film CdTe solar cells. *Thin Solid Films*. 2006;510(1-2):320-324. https://doi.org/10.1016/j.tsf.2006.01.004

12. Williams RH, Patterson MH. Fermi level pinning at metal-CdTe interfaces. *Appl Phys Lett*. 1982;40(6):484-486. https://doi.org/10.1063/1.93151

13. Platzer-Björkman C, Barreau N, Bär M, et al. Back and front contacts in Kesterite solar cells: state-of-the-art and open questions. *J Phys Energy*. 2019;1(4):044005. https://doi.org/10.1088/2515-7655/ab3708

14. Karade V, Lokhande A, Babar P, et al. Insights into Kesterite’s back contact interface: a status review. *Sol Energy Mater Sol Cells*. 2019;200:109911. https://doi.org/10.1016/j.solmat.2019.04.033

15. Pitchaiya S, Natarajan M, Santhanam A, et al. A review on the classification of organic/inorganic/carbonaceous hole transporting materials for perovskite solar cell application. *Arabian J Chem*. 2020;13(1):2526-2557. https://doi.org/10.1016/j.arabjc.2018.06.006

16. Kharangar P, Misra D, Georgiou GE, Chin KK. Evaluation of Cu back contact related deep defects in CdTe solar cells. *ECS J Sol State Sci Technol*. 2012;1(5):Q110-Q113. https://doi.org/10.1149/2.001206jss

17. Capper P, ed. Properties of Narrow Gap Cadmium-Based Compounds. EMIS Datasreviews Series. London: Institution of Electrical Engineers, INSPEC; 1994.

18. McCandless BE, Sites JR. Chapter 14: Cadmium telluride solar cells. In: Luque López A, Hegedus S, eds. *Handbook of Photovoltaic Science and Engineering*. Chichester: Wiley; 2011.

19. Kumar SG, Rao KSRK. Physics and chemistry of CdTe/CdS thin film heterojunction photovoltaic devices: fundamental and critical aspects. *Energy Environ Sci*. 2014;7(1):45-102. https://doi.org/10.1039/C3EE41981A

20. Znajdek K, Sibinski M, Kubiak A, Ruta L, Lisik Z, Janczak D. Analysis of back contact layers for flexible CdTe/CdS photovoltaic structures. *Opto-Electron Rev*. 2019;27(1):32-38. https://doi.org/10.1016/j.opere.2018.12.001

21. Chou HC, Rohatgi A, Jokerst NM, Thomas EW, Kamra S. Copper migration in CdTe heterojunction solar cells. *JEM*. 1996;25(7):1093-1098. https://doi.org/10.1016/BF02659909

22. Phillips AB, Khanal RR, Song Z, et al. Wiring-up carbon single wall nanotubes to polycrystalline inorganic semiconductor thin films: low-barrier, copper-free back contact to CdTe solar cells. *Nano Lett*. 2013;13(11):5224-5232. https://doi.org/10.1021/nl402659c

23. Demets S, Albin D, Sites J. Role of copper in the performance of CdS/CdTe solar cells. In: 2006 IEEE 4th World Conference on Photovoltaic Energy Conference. Waikoloa Village, HI: IEEE; 2006:523-526. https://doi.org/10.1109/WCPEC.2006.279507

24. Meyers PV, Liu CH, Russell L, et al. Polycrystalline CdTe on CuInSe2 cascaded solar cells. In: Conference Record of the Twentieth IEEE Photovoltaic Specialists Conference, Vol. 2. Las Vegas, NV: IEEE; 1988:1448-1451. https://doi.org/10.1109/PVSC.1988.105949

25. Cousins MA, Lane DW, Rogers KD. Sulphur diffusion in cadmium telluride thin films part 2: modelling grain-boundary diffusion. *Thin Solid Films*. 2003;431-432:78-83. https://doi.org/10.1016/S0040-6090(03)00206-2

26. Abbas A, Swanson D, Munshi A, et al. The effect of a post-activation annealing treatment on thin film CdTe device performance. In: 2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC). New Orleans, LA: IEEE; 2015:1-6. https://doi.org/10.1109/PVSC.2015.7356441

27. Liyanage GK, Phillips AB, Alfadhlhi FK, Ellingson RJ, Heben MJ. The role of back buffer layers and absorber properties for >25% efficient CdTe solar cells. *ACS Appl Energy Mater*. 2019;2(8):5419-5426. https://doi.org/10.1021/acsaeem.9b00367

28. Burgelman M, Nollet P, Degrave S. Modelling polycrystalline semiconductor solar cells. *Thin Solid Films*. 2000;361-362:527-532. https://doi.org/10.1016/S0040-6090(99)00825-1

29. Anthony TC, Fahrenbruch AL, Bube RH. Low resistance contacts to p-type cadmium telluride. *JEM*. 1982;11(1):89-109. https://doi.org/10.1016/0021-6913(82)90061-7

30. Haring J-P, Werthen JG, Bube RH, Gulbranssen L, Jansen W, Luscher P. Study of cleaved, oxidized, etched, and heat-treated CdTe surfaces. *J Vac Sci Technol A*. 1983;1(3):1469-1472. https://doi.org/10.1116/1.572170

31. Rimmaudo I, Salavei A, Artigiani E, et al. Improved stability of CdTe solar cells by absorber surface etching. *Sol Energy Mater Sol Cells*. 2017;162:127-133. https://doi.org/10.1016/j.solmat.2016.12.044

32. Awni RA, Grice CR, Li D, Song Z, Yan Y. Electrical impedance characterization of CdTe thin film solar cells with hydrogen iodide back surface etching. In: 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC). Waikoloa Village, HI: IEEE; 2018:1878-1881. https://doi.org/10.1109/PVSC.2018.8548289

33. Awni RA, Li D-B, Grice CR, et al. The effects of hydrogen iodide back surface treatment on CdTe solar cells. *Sol RRL*. 2019;3(3):1800304. https://doi.org/10.1002/solr.201800304

34. Li X, Niles DW, Hasoon FS, Matson RJ, Sheldon P. Effect of nitric-phosphoric acid etches on material properties and back-contact formation of CdTe-based solar cells. *J Vac Sci Technol A*. 1999;17(3):805-809. https://doi.org/10.1116/1.581651

35. Yan Y, Jones KM, Wu X, Al-Jassim MM. Microstructure of CdTe thin films after mixed nitric and phosphoric acids etching and (HgTe, CuTe)-graphite pasting. *Thin Solid Films*. 2005;472(1-2):291-296. https://doi.org/10.1016/j.tsf.2004.07.002

36. Song T, Sites JR. Role of tellurium buffer layer on CdTe solar cells' absorber/back-contact interface. In: 2017 IEEE 44th Photovoltaic Specialist Conference (PVSC). Washington, DC: IEEE; 2017:1308-1311. https://doi.org/10.1109/PVSC.2017.8366848

37. Proskuryakov YY, Durose K, Taclc BM, Welch GP, Oelting S. Admittance spectroscopy of CdTe/CdS solar cells subjected to varied nitric-phosphoric etching conditions. *J Appl Phys*. 2007;101(1):014505. https://doi.org/10.1063/1.2402961

38. Majid JD, Treharne RE, Phillips LJ, Durose K. A low-cost non-toxic post-growth activation step for CdTe solar cells. *Nature*. 2014;511(7509):334-337. https://doi.org/10.1038/nature13435
39. Hsiao K-J, Sites JR. Electron reflector strategy for CdTe solar cells. In: 2009 34th IEEE Photovoltaic Specialists Conference (PVSC). Philadelphia, PA: IEEE; 2009:1846-1850. https://doi.org/10.1109/PVSC.2009.5411531

40. Hsiao K-J, Sites JR. Electron reflector to enhance photovoltaic efficiency: application to thin-film CdTe solar cells: proposed electron reflector for CdTe solar cells. Prog Photovolt Res Appl. 2012;20(4):486-489. https://doi.org/10.1002/pip.1143

41. Swanson DE, Abbas A, Munshi AH, et al. Incorporation of Cu$_x$Mg$_{1-x}$Te as an electron reflector for cadmium telluride photovoltaic cells. MRS Proc. 2015;1771:133-138. https://doi.org/10.1557/opl.2015.389

42. Ponpon JP. A Review of ohmic and rectifying contacts on cadmium telluride. Solid-State Electron. 1985;28(7):689-706. https://doi.org/10.1016/0038-1098(85)90019-X

43. Kaufmann U, Windscheif J, Brunthaler G. Identification of the isolated deep Ni acceptor in CdTe and ZnTe: comparison with isomorphous systems. J Phys C: Solid State Phys. 1984;17(34):6169-6176. https://doi.org/10.1088/0022-3719/17/34/017

44. Niles DW, Li X, Sheldon P, Höchst H. A photoemission determination of the band diagram of the Te/CdTe interface. J Appl Phys. 1995;77(9):4489-4493. https://doi.org/10.1063/1.359444

45. Niles DW, Li X, Sheldon P, Höchst H. A photoemission determination of the band diagram of the Te/CdTe interface. J Appl Phys. 1995;77(9):4489-4493. https://doi.org/10.1063/1.359444

46. Niles DW, Li X, Albin D, Rose D, Gessert T, Sheldon P. Evaporated Te on CdTe: a vacuum-compatible approach to making back contact to CdTe solar cell devices. Prog Photovolt Res Appl. 1996;4(3):225-229. https://doi.org/10.1002/(SICI)1099-159X(199605/06)4:3<225::AID-PIP1223|2.0.CO;2-6

47. Niles DW, Li X, Albin D, Rose D, Gessert T, Sheldon P. Evaporated Te on CdTe: a vacuum-compatible approach to making back contact to CdTe solar cell devices. Prog Photovolt Res Appl. 1996;4(3):225-229. https://doi.org/10.1002/(SICI)1099-159X(199605/06)4:3<225::AID-PIP1223|2.0.CO;2-6

48. Kraft D, Thissen A, Broetz J, et al. Characterization of tellurium layers for back contact formation on close to technology treated CdTe surfaces. J Appl Phys. 2003;94(5):3589-3598. https://doi.org/10.1063/1.1597757

49. Moffett CE, Sampath WS. Characterization of tellurium as a back contact for CdTe solar cells. In: 2017 IEEE 44th Photovoltaic Specialist Conference (PVSC). Washington, DC: IEEE; 2017:2736-2739. https://doi.org/10.1109/PVSC.2017.8366272

50. Munshi AH, Kephart JM, Abbas A, et al. Polycrystalline CdTe photovoltaics with efficiency over 18% through improved absorber passivation and current collection. Sol Energy Mater Sol Cells. 2018;176:183-188. https://doi.org/10.1016/j.solmat.2017.11.031

51. Alladihilii FK, Phillips AB, Liyanage GK, Gibbs JM, Jamarkattel MK, Heben MJ. Controlling band alignment at the back interface of cadmium telluride solar cells using ZnTe and Te buffer layers. MRS Adv. 2019;4(16):913-919. https://doi.org/10.1057/adv.2019.31

52. Perrenoud J, Kranz L, Gretener C, et al. A comprehensive picture of Cu doping in CdTe solar cells. J Appl Phys. 2013;114(17):174505. https://doi.org/10.1063/1.4828484

53. Ferekides CS, Viswanathan V, Morel DL. RF sputtered back contacts for CdTe/Cds thin film solar cells. In: Conference Record of the Twenty Sixth IEEE Photovoltaic Specialists Conference - 1997; PVSC. Vol. 26. Anaheim, CA: IEEE; 1997:423-426. https://doi.org/10.1109/PVSC.1997.654118

54. McCandless BE, Hegedus SS, Birkmire RW, Cunningham D. Correlation of surface phases with electrical behavior in thin-film CdTe devices. Thin Solid Films. 2003;431-432:249-256. https://doi.org/10.1016/S0040-6090(03)00266-9

55. Avachat US. Development of Transparent and Conducting Back Contacts on CdS/CdTe Solar Cells for Photoelectrochemical Application. Masters thesis. USA: University of Central Florida; 2005.

56. Wu X, Zhou J, Duda A, et al. Phase control of Cu$_x$Te film and its effects on CdS/CdTe solar cell. Thin Solid Films. 2007;515(15):5798-5803. https://doi.org/10.1016/j.tsf.2006.12.151

57. Zhou J, Wu X, Duda A, Teeter G, Demitsu SH. The formation of different phases of Cu$_x$Te and their effects on CdTe/CdS solar cells. Thin Solid Films. 2007;515(18):7364-7369. https://doi.org/10.1016/j.tsf.2007.03.032

58. Moore A. Performance and Metastability of CdTe Solar Cells with a Te Back-Contact Buffer Layer. PhD thesis. Fort Collins, CO: Colorado State University; 2017.

59. Bosio A, Cipriani R, Lamperti A, et al. Interface phenomena between CdTe and ZnTe/Cu back contact. Sol Energy, 2018;176:186-193. https://doi.org/10.1016/j.solener.2018.10.035

60. Li J, Diercks DR, Ohno TR, et al. Controlled activation of ZnTe/Cu contacted CdTe solar cells using rapid thermal processing. Sol Energy Mater Sol Cells. 2015;133:208-215. https://doi.org/10.1016/j.solmat.2014.10.045

61. Janik E, Triboulet R. Ohmic contacts to P-type cadmium telluride and cadmium mercury telluride. J Phys D: Appl Phys. 1983;16(12):2333-2340. https://doi.org/10.1088/0023-0180/16/12/011

62. Zoizme A, Vermeulin C. Properties of sputtered mercury telluride contacts on P-type cadmium telluride. Rev Phys Appl (Paris). 1988;23(11):1825-1835. https://doi.org/10.1051/physap0198800230110182500

63. Britt JS, Ferekides CS.U5557146A - Ohmic Contact Using Binder Paste with Semiconductor Material Dispersed Therein. US5557146A.

64. Duenow JN, Dhere RG, Li JV, Young MR, Gessert TA. Effects of back-contacting method and temperature on CdTe/CdS solar cells. In: 2010 35th IEEE Photovoltaic Specialists Conference. Honolulu, HI: IEEE; 2010:1001-1005. https://doi.org/10.1109/PVSC.2010.5614593

65. Wu X, Keane JC, Dhere RG, et al. 16.5%-efficient CdS/CdTe polycrystalline thin-film solar cells. In: 17th EU-PVSEC; Munich, Germany; 2001:995-1000.

66. Hanafusa A, Aramoto T, Morita A. Performance of graphite pastes doped with various materials as back contact for CdS/CdTe solar cell. Jpn J Appl Phys. 2001;40(1, No. 12):6764-6769. https://doi.org/10.1143/JJAP.40.6764

67. Adachi S. Optical Constants of Crystalline and Amorphous Semiconductors. Boston, MA: Springer US; 1999. https://doi.org/10.1007/978-1-4615-5247-5

68. Van de Walle CG, Laks DB. Nitrogen doping in ZnSe and ZnTe. Sol State Commun. 1995;93(5):447-450. https://doi.org/10.1016/0038-1098(94)00815-9
84. Rotlevi O, Ishii H, Toda T, Niina T. Growth and characterization of MBE-grown ZnTe:P. J Cryst Growth. 1989;95(1-4):517-521. https://doi.org/10.1016/0022-0248(89)90456-9

87. Dhar N, Chowdhury TH, Islam MA, et al. Effect of N-type transition metal dichalcogenide molybdenum telluride (n-MoTe2) in back contact interface of cadmium telluride solar cells from numerical analysis. Chalcog Lett. 2014;11(6):271-279.

88. Moustafa M, Alzoubi T. Numerical study of CdTe solar cells with p-MoTe2 TMDC as an interfacial layer using SCAPS. Mod Phys Lett B. 2018;32(23):1850269. https://doi.org/10.1142/S021798491850269X
J Mater Chem C. 2017;5(20):4996-5004. https://doi.org/10.1039/C7TC00948H

135. Pitchaiya S, Natarajan M, Santhanam A, et al. Nickel sulphide-carbon composite hole transporting material for (CH$_3$NH$_3$)$_2$PbI$_3$ planar heterojunction perovskite solar cell. Mater Lett. 2018;221:283-288. https://doi.org/10.1016/j.matlet.2018.03.161

136. Subedi KK, Bastola E, Subedi I, et al. Bifacial CdS/CdTe solar cell using transparent barium copper sulphide as a hole transport layer. In: 2019 IEEE 46th Photovoltaic Specialists Conference (PVSC). Chicago, IL: IEEE; 2019:4. https://doi.org/10.1109/PVSC40753.2019.8989036

137. Tan X. Applications of Multichannel Spectroscopic Ellipsometry for CdTe Photovoltaics: From Window Layers to Back Contacts. PhD. University of Toledo, USA; 2017.

138. Yuan S, Zhang M-J, Yang X, Mei Z, Chen Y, Pan F. A novel MoS$_2$-based hybrid film as the back electrode for high-performance thin film solar cells. RSC Adv. 2017;7(38):23415-23421. https://doi.org/10.1039/C7RA03233A

139. Deng X-Z, Zhang J-R, Zhao Y-Q, Yu Z-L, Yang J-L, Cai M-Q. The transparency of the intermediate solar cell in multi-junction solar cells. Thin Solid Films. 2009;517(7):2340-2343. https://doi.org/10.1016/j.tsf.2008.11.007

140. Gong C, Colombo L, Wallace RM, Cho K. The unusual mechanism of partial fermi level pinning at metal–MoS$_2$ interfaces. Nano Lett. 2014;14(4):1714-1720. https://doi.org/10.1021/nl403465v

141. Clayton AJ, Baker MA, Babar S, et al. Effects of Cd$_{1-x}$Zn$_x$S alloy composition and post-deposition air anneal on ultra-thin CdTe solar cells produced by MOCVD. Mater Chem Phys. 2017;192:244-252. https://doi.org/10.1016/j.matchemphys.2017.01.067

142. Major JD. Grain boundaries in CdTe thin film solar cells: a review. Semicond Sci Technol. 2016;31(9):093001. https://doi.org/10.1088/1361-648X/ab4013

143. Crossay A, Buecheler S, Kranz L, et al. Spray-deposited Al-doped ZnO transparent contacts for CdTe solar cells. Sol Energy Mater Sol Cells. 2012;101:283-288. https://doi.org/10.1016/j.solmat.2012.02.008

144. Parikh VY. Studies of Two-Terminal and Four-Terminal Polycrystalline Thin Film Tandem Solar Cells Based on II-VI Materials. PhD. University of Toledo, USA; 2007.

145. Heisler C, Schnohr CS, Hädrich M, et al. Transparent CdTe solar cell using transparent barium copper sulphide as a hole transport layer. In: 2019 IEEE 46th Photovoltaic Specialists Conference (PVSC). Chicago, IL: IEEE; 2019:4. https://doi.org/10.1109/PVSC40753.2019.8989036

146. Crisp RW, Panthani MG, Rance WL, et al. Nanocrystal grain growth and device architectures for high-efficiency CdTe ink-based photovoltaics. ACS Nano. 2014;8(9):9063-9072. https://doi.org/10.1021/nn502442g

147. Guo Y, Robertson J. Origin of the high work function and high conductivity of MoO$_x$. Appl Phys Lett. 2014;105(22):222110. https://doi.org/10.1063/1.4903538

148. Crossay A, Buecheler S, Kranz L, et al. Spray-deposited Al-doped ZnO transparent contacts for CdTe solar cells. J Vac Sci Technol A. 2014:2397-2399. https://doi.org/10.1109/PVSC.2014.6925410

149. Crisp RW, Panthani MG, Rance WL, et al. Nanocrystal grain growth and device architectures for high-efficiency CdTe ink-based photovoltaics. ACS Nano. 2014;8(9):9063-9072. https://doi.org/10.1021/nn502442g
166. Xiao D, Li X, Wang D, Li Q, Shen K, Wang D. CdTe thin film solar cell with NiO as a back contact buffer layer. Sol Energy Mater Sol Cells. 2017;169:61-67. https://doi.org/10.1016/j.solmat.2017.05.006

167. Owings RR, Exarhos GJ, Windisch CF, Holloway PH, Wen JG. Process enhanced polaron conductivity of infrared transparent nickel-cobalt oxide. Thin Solid Films. 2005;483(1–2):175-184. https://doi.org/10.1016/j.tsf.2005.01.011

168. Tiefenbacher S, Pettenkofer C, Jaegermann W. Ultrahigh vacuum preparation and characterization of TiO2/CdTe interfaces: electrical properties and implications for solar cells. J Appl Phys. 2002;91(4):1984-1987. https://doi.org/10.1063/1.1435413

169. Brus TV, Ilaschchuk MI, Kovalyuk ZD, Maryanchuk PD. Light-dependent I-V characteristics of TiO2/CdTe heterojunction solar cells. Semicond Sci Technol. 2012;27(5):055008. https://doi.org/10.1088/0268-1242/27/5/055008

170. Schwarz R, Joerger W, Eiche C, Fiederle M, Benz KW. Closed tube vapour growth of CdTe:V and CdTe:Ti and its characterization. J Cryst Growth. 1995;146(1–4):92-97. https://doi.org/10.1006/jcrg.2002.2494

171. Uličná S, Arnou P, Abbas A, et al. Deposition and application of Al2O3-based surface passivation schemes for silicon solar cells. J Vac Sci Technol A. 2012;30(4):040802. https://doi.org/10.1116/1.4728205

172. Verma Y, Wätjen JT, Fjällström V, et al. Employing Si solar cell technology to increase efficiency of ultra-thin Cu(In, Ga)S2 cells: employing Si solar cell technology. Prog Photovolt Res Appl. 2014;22(10):1023-1029. https://doi.org/10.1002/pip.2527

173. Viswanathan V, Tetali B, Selvaraj P, et al. Ni2P-a promising candidate for back contacts to CdS/CdTe solar cells. In: Andresen BF, Fulop GF, Norton PR, eds. Proceedings of the Twenty-Eighth IEEE Photovoltaic Specialists Conference - 2000 (Cat. No.00CH37036). Washington, DC: IEEE; 2000:805616

174. Owings RR, Exarhos GJ, Windisch CF, Holloway PH, Wen JG. Band alignment for rectification and tunneling effects in Al2O3 atomic-layer-deposited on back contact for CdTe solar cell. J Mater Chem A. 2019;7(12):7042-7052. https://doi.org/10.1039/C9TA01208G

175. Su Y, Xin C, Feng Y, et al. Band alignment for rectification and tunneling effects in Al2O3 atomic-layer-deposited on back contact for CdTe solar cell. ACS Appl Mater Interfaces. 2016;8(41):28143-28148. https://doi.org/10.1021/acsami.6b07421

176. Liang J, Lin Q, Li H, et al. Rectification and tunneling effects enabled by Al2O3 atomic layer deposited on back contact of CdTe solar cells. Appl Phys Lett. 2015;107(1):013907. https://doi.org/10.1063/1.4926601

177. Lin Q, Su Y, Zhang M-J, et al. A novel P-type and metallic dual-functional Cu–Al2O3 ultra-thin layer as the back electrode enabling high performance of thin film solar cells. Chem Commun. 2016;52(71):10708-10711. https://doi.org/10.1039/C6CC04299F

178. Munshi AH, Danielson AH, Kindvall A, Barth K, Sampath W. Investigation of sputtered oxides and p+ back-contact for polycrystalline CdTe and CdSeTe photovoltaics. In: 2018 IEEE 9th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC). Waikoloa Village, HI: IEEE; 2018;3009-3012. https://doi.org/10.1109/PVSC.2018.8548203

179. Meyer BK, Polity A, Reppin D, et al. Binary copper oxide semiconductors: from materials towards devices. Phys Stat Sol B. 2012;249(8):1487-1509. https://doi.org/10.1002/pssb.201248128

180. Spies JA. Inorganic Thin-Film Solar Cells. Masters thesis. OR, USA: Oregon State University; 2007.

181. Yamamoto K, Okamoto H, Sakakima H, et al. Fabrication of transparent P-type conductive BaCuSeF films by pulsed laser deposition and their application to CdS/CdTe solar cells. Jpn J Appl Phys. 2014;53(5S1):05FX02. https://doi.org/10.1109/JPHOTOV.2017.7856271
194. Yamamoto K, Sakakima H, Ogawa Y, Hosono A, Okamoto T, Wada T. Fabrication of CdS/CdTe solar cells with transparent p-type conductive BaCuSeF back contact. *Jpn J Appl Phys*. 2015;54(8S1):08KC01. https://doi.org/10.7567/JJAP.54.08KC01

195. Kitabayashi S, Shinya Y, Murata A, Okamoto T, Wada T. Fabrication of P-type SrCuSeF/n-type In$_2$O$_3$:Sn bilayer ohmic tunnel junction and its application to the back contact of CdS/CdTe solar cells. *Jpn J Appl Phys* 2017;56(8S2):08MC18. https://doi.org/10.7567/JIAP.56.08MC18

196. Wada T, Kiki K, Tamai D, et al. Fabrication of P-type Na doped SrCuSeF & n-type ITO bilayer ohmic tunnel junction as back contact of CdTe SC. *EU-PVSEC*. 2018:35:3BV.2.36.

197. Miki K, Kawabe T, Shinya Y, Okamoto S, Okamoto T, Wada T. Fabrication of P-type BaCuSF and n-Type In$_2$O$_3$:Sn bilayer films and their applications to the back contact of CdS/CdTe solar cells. *Jpn J Appl Phys*. 2018;57(8S3):08RC19. https://doi.org/10.7567/JJAP.57.08RC19

198. Bhandari KP, Watthage SC, Song Z, et al. Applications of hybrid organic-inorganic metal halide perovskite thin film as a hole transport layer in CdTe thin film solar cells. In: *2017 IEEE 44th Photovolatic Specialist Conference (PVSC)*. Washington, DC: IEEE; 2017:748-751. https://doi.org/10.1109/PVSC.2017.8366784

199. Liyanage GK, Phillips AB, Alfadhili FK, et al. Modeling the performance of CdTe solar cells with a CH$_3$NH$_3$Pb(I$_{1-x}$Br$_x$)$_3$ perovskite as the back contact for CdS/CdTe solar cells. *Prog Photovolt Res Appl*. 2019;27(8):706-715. https://doi.org/10.1002/pip.3148

200. Shi Z, Jayatissa A. The impact of graphene on the fabrication of thin film solar cells: current status and future prospects. *Mater*. 2017;11(1):36. https://doi.org/10.3390/ma11010036

201. Shi Z, Jayatissa A. The impact of graphene on the fabrication of thin film solar cells: current status and future prospects. *Mater*. 2017;11(1):36. https://doi.org/10.3390/ma11010036

202. Arora N, Dar MI, Hinderhofer A, et al. Perovskite solar cells with CuSCN hole extraction layers yield stabilized efficiencies greater than 20%. *Science*. 2017;358(6364):768-771. https://doi.org/10.1126/science.aan5655

203. Pressman AB. *Electrical Properties of Cadmium Telluride Thin Film Solar Cells Activated with Magnesium Chloride*. PhD. University of Liverpool, UK; 2017.

204. Montgomery A, Guo L, Grice C, et al. Solution-processed copper(I) thiocyanate (CuSCN) hole-transport layers processed from aqueous precursor solutions and their application in thin-film transistors and highly efficient organic and organometal halide perovskite solar cells. *Adv Funct Mater*. 2017;27(35):1701818. https://doi.org/10.1002/adfm.201701818

205. Arora N, Dar MI, Hinderhofer A, et al. Perovskite solar cells with CuSCN hole extraction layers yield stabilized efficiencies greater than 20%. *Science*. 2017;358(6364):768-771. https://doi.org/10.1126/science.aan5655

206. Montgomery A, Guo L, Grice C, et al. Solution-processed copper(I) thiocyanate (CuSCN) for highly efficient CdSe/CdTe thin-film solar cells. *Prog Photovolt Res Appl*. 2019;27:665-672. https://doi.org/10.1002/pip.3136

207. Yan F, Guo L, Montgomery A. Application of solution-processed CuSCN and AgSCN for highly efficient Cdt solar cells. In: *PVSC*. Chicago, IL: IEEE; 2019.

208. Cohen R, Bastide S, Cahen D, Libman J, Shanzer A, Rosenwaks Y. Controlling electronic properties of CdTe by adsorption of dicarboxylic acid derivatives: relating molecular parameters to band bending and electron affinity changes. *Adv Mater*. 1997;9(9):746-749. https://doi.org/10.1002/adma.19970090915

209. Cohen R, Bastide S, Cahen D, Libman J, Shanzer A, Rosenwaks Y. Controlling surfaces and interfaces of semiconductors using organic molecules. *Opt Mater*. 1999;9(1-4):394-400. https://doi.org/10.1016/S0925-3467(97)00065-7

210. Jarkov A, Bereznev S, Volobujeva O, et al. Photo-assisted electrodeposition of polypyrrole back contact to CdS/CdTe solar cell structures. *Thin Solid Films*. 2013;535:198-201. https://doi.org/10.1016/j.tsf.2013.01.064
224. Du X, Chen Z, Liu F, et al. Improvement in open-circuit voltage of thin film solar cells from aqueous nanocrystals by interface engineering. *ACS Appl Mater Interfaces*. 2016;8(1):900-907. https://doi.org/10.1021/acsami.5b10374

225. Shalvey TP, Phillips LJ, Durose K, Major JD. A comparison of organic back contact materials for CdTe solar cells. In *2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC)*. Waikoloa Village, HI; IEEE: 2018:846-851. https://doi.org/10.1109/PVSC.2018.8547725

226. Major JD, Phillips LJ, Al Turkestani M, et al. P3HT as a pin-hole blocking back contact for CdTe thin film solar cells. *Solar Energy Mater Sol Cells*. 2017;172:1-10. https://doi.org/10.1016/j.solmat.2017.07.005

227. Wei H, Fang Y, Yuan Y, Shen L, Huang J. Trap engineer - Major JD, Phillips LJ, Al Turkestani M, et al. P3HT as a pin-hole blocking back contact for CdTe thin film solar cells. *Solar Energy Mater Sol Cells*. 2017;172:1-10. https://doi.org/10.1016/j.solmat.2017.07.005

228. Ke W, Zhao D, Grice CR, Cimaroli AJ, Fang G, Yan Y. Efficient Hole transporting materials for perovskite solar cells: a chemical approach. *Chem Soc Rev*. 2018;47(23):8541-8571. https://doi.org/10.1039/C8CS00262B

229. Kim S, Jeon J, Suh J, et al. Comparative study of Cu2Te and Cu back contact in CdS/CdTe solar cell. *J Kor Phys Soc*. 2018;72(7):780-785. https://doi.org/10.3938/jkps.72.780

230. Makhratchev K, Price KJ, Ma X, et al. ZnTe:N back contacts to CdS/CdTe solar cells. In: *Conference Record of the Twenty-Eighth IEEE Photovoltaic Specialists Conference - 2000 (Cat. No. No.00CH37036)*. Anchorage, AK: IEEE; 2000:475-478. https://doi.org/10.1109/PVSC.2000.9158784

231. Paudel NR, Yan Y. Sputtered CdS/CdTe solar cells with a PCBM back contact. *Improved Performance CdTe Solar Cells Final Report*; DE-EE0005405, 1433077; 2018; p DE–EE0005405, 1433077. https://doi.org/10.1021/acsnanlett.5b04510

232. Hodges DR. *Development of CdTe Thin Film Solar Cells on Flexible Foil Substrates*. PhD thesis. University of South Florida; 2009.

233. Hu S, Zhu Z, Li W, et al. Band diagrams and performance of CdTe solar cells with a Sb2Te3 back contact buffer layer. *AIP Adv*. 2011;1(4):042152. https://doi.org/10.1063/1.3636313

234. Emziane M, Durose K, Halliday DP, Bosio A, Romeo N. Efficiency improvement in thin-film solar cell devices with oxygen-containing absorber layer. *Appl Phys Lett*. 2005;87(26):261901. https://doi.org/10.1063/1.2152108

235. Zhang M-J, Lin Q, Yang X, et al. Novel P-type conductive semiconductor nanocrystalline film as the back electrode for high-performance thin film solar cells. *Nano Lett*. 2016;16(12):1218-1223. https://doi.org/10.1021/acs.nanolett.5b04510

236. Rockett A, Marsillac S, Collins R. *Novel Contact Materials for Improved Performance CdTe Solar Cells Final Report*; DE-EE0005405, 1433077; 2018; p DE–EE0005405, 1433077. https://doi.org/10.1021/1271433077

237. Yang R, Wang D, Jeng M, Ho K, Wang D. Stable CdTe thin film solar cells with a MoOx back contact buffer layer. *Prog Photovolt Res Appl*. 2016;24(1):59-65. https://doi.org/10.1002/pip.2645

238. Wang D, Yang R, Wu L, Shen K, Wang D. Band alignment of CdTe with MoOx oxide and fabrication of high efficiency CdTe solar cells. *Sol Energy*. 2018;162:637-645. https://doi.org/10.1016/j.solener.2018.01.031

239. Paudel NR, Compaan AD, Yan Y. Sputtered CdS/CdTe solar cells with MoOx−x/Au back contacts. *Sol Energy Mater Sol Cells*. 2013;113:26-30. https://doi.org/10.1016/j.solmat.2013.01.041
251. Irfan I, Lin H, Xia W, Wu HN, Tang CW, Gao Y. The effect of MoOx inter-layer on thin film CdTe/CdS solar cell. *Sol Energy Mater Sol Cells*. 2012;105:86-89. https://doi.org/10.1016/j.solmat.2012.04.006

252. Dang H, Singh VP. Nanowire CdS-CdTe solar cells with molybdenum oxide as contact. *Sci Rep*. 2015;5(1):14859. https://doi.org/10.1038/srep14859

253. Khrypunov MG, Kudii DA, Koptun NA, Kharchenko MM, Khrypunova IV. Development of back and front contacts for CdTe layer in tandem flexible photoelectric converters on basis of CdTe/CuInSe2. *Internat J Photoenergy*. 2019;2019:1-8. https://doi.org/10.1155/2019/9535123

254. Wu X, Zhou J, Duda A, et al. 13.9%-efficient CdTe polycrystalline thin-film solar cells with an infrared transmission of ~50%. *Prog Photovolt Res Appl*. 2006;14(6):471-483. https://doi.org/10.1002/pip.664

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