Barrier/bonding layers on bismuth telluride (Bi₂Te₃) for high temperature thermoelectric modules

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Abstract In this research, a fundamental study is conducted to identify the materials and develop the processes for producing barrier/bonding composite on Bi₂Te₃ for high temperature thermoelectric applications. The composite must meet four basic requirements: (a) prevent inter-diffusion between the electrode material, for our design, silver(Ag) and Bi₂Te₃, (b) bond well to Bi₂Te₃, (c) bond well to Ag electrode, and (d) do not themselves diffuse into Bi₂Te₃. The composites investigated include palladium (Pd), nickel/gold (Ni/Au), Ag, and titanium/gold (Ti/Au). After annealing at 250 °C for 200 h, only the Ti/Au design meets all four requirements. The thickness of Ti and Au, respectively, is only 100 nm. Other than meeting these four requirements, the Ti/Au layers exhibit excellent step coverage on the rough Bi₂Te₃ surface even after the annealing process.

1 Introduction

Bismuth telluride (Bi₂Te₃) is a narrow band gap semiconductor with tragonal unit cell. It was first investigated as a thermoelectric (TE) material in 1950s [1–3]. The TE power generator uses Seebeck effect to convert temperature gradient ΔT into electrical power. The voltage produced is given by \( V = \alpha \Delta T \), where \( \alpha \) is Seebeck coefficient. Conversely, the TE cooler uses the Peltier effect to convert electrical power into temperature gradient by transporting heat from cold side to hot side. The heat transported is given by \( Q_p = \pi I \), where \( I \) is the current and \( \pi \) is the Peltier coefficient. Bi₂Te₃ is so far the most popular TE material.

Alloying with Sb₂Te₃ and Bi₂Se₃ can control carrier concentrations alongside a reduction in lattice thermal conductivity [4]. It can also improve the figure-of-merit, \( Z = \alpha^2 (\sigma T / \kappa) \), where \( \sigma \) is the electrical conductivity and \( \kappa \) is its thermal conductivity. Bismuth-based alloys with antimony, tellurium, and selenium are referred to as low-temperature materials with \( Z \) around 2 × 10⁻³ K⁻¹ and can be used at temperature up to 450 K [5]. For temperature from 450 to 850 K, the most common thermoelectric material is lead telluride. At even higher temperature, silicon germanium alloys can operate up to 1,300 K [4, 5]. Z of lead telluride and silicon germanium alloy are below 2 × 10⁻³ K⁻¹ [5]. Most TE devices on the market are made of Bi₂Te₃-based alloys.

A TE cooler or generator, portrayed in Fig. 1, is constructed of an array of p-type and n-type TE columns bonded between two ceramic plates [6]. These columns are connected electrically in series to form a chain of p-n junctions but thermally in parallel. Solder is employed to bond the TE columns to the ceramic plates. TE modules on the market have a maximum operating temperature of 80 °C on the hot side [7]. This constraint prohibits numerous applications and economic opportunities where higher operation temperature is required. An example is to cool the transistor in the front-end amplifier of an outdoor wireless communications base station to reduce its noise. Another example is to cool the front-end photodiode of a military laser range-finding receiver to increase its sensitivity. The 80 °C limit is imposed by severe diffusion of...
solder material into the TE materials rather than by TE materials themselves. The melting points of TE materials Bi$_2$Te$_3$, Sb$_2$Te$_3$, and Bi$_2$Se$_3$ are 585 °C [8], 618 °C [9], and 706 °C [10], respectively. Therefore, to extend the operating temperature to 150 °C, solder diffusion at high temperature must be stopped. Accordingly, high temperature bonding/barrier layers must be investigated and identified.

Several groups had studied diffusion barrier for Bi$_2$Te$_3$ and copper (Cu) interconnect. Few showed positive results. In one study, Ni was used as a diffusion-barrier for tin (Sn) in both (Bi,Sb)$_2$Te$_3$ and Bi$_2$(Te,Se)$_3$ [11]. Ni diffuses into Bi$_2$(Te,Se)$_3$ by several microns during the soldering process. Ni was also found to diffuse into Bi$_2$(Te,Se)$_3$ and form a nickel telluride interfacial region after heat treatment at 200 °C [12]. In another study, Ni-7% vanadium (V), Pd and platinum (Pt) films were used but failed to prevent inter-diffusion between Cu and Bi$_2$Te$_3$ after annealing at 200 °C for a few hours [13]. It is clear that several research groups had searched for diffusion barrier on Bi$_2$Te$_3$-based compounds. So far, the best barrier design can sustain 200 °C only for a few hours.

The objective of this research is to design and develop barrier/bonding composite that can sustain annealing at 250 °C for 200 h. The composite is fabricated between Bi$_2$Te$_3$-based compound and Ag electrode. One surface of the composite must bond to Bi$_2$Te$_3$-compound and the other surface must bond to Ag. Furthermore, it must prevent Ag atoms from diffusing into Bi$_2$Te$_3$ and prevent Bi$_2$Te$_3$ from diffusing into Ag electrode. Ag rather than Cu is chosen as the electrode material because it has the highest electrical conductivity and thermal conductivity among metals. To identify the right bonding/barrier materials and processes, we went through a systematic study, starting with Pd, followed by Ni/Au, Ag, and Ti/Au. Some preliminary results were presented in [14]. In this paper, we report more complete analyses and results. Additional information obtained includes: extensive 250 °C annealing data of Ti/Au barrier/bonding layer from 10 to 200 h, Ag surface morphology and adhesion on different barrier layers, SEM/EDX analyses on inter-diffused regions, and discussion on compound formation in inter-diffused regions.

In what follows, experimental design and procedure are presented. Experimental results are reported and discussed. A short summary is then given. For convenience, all chips made of Bi$_2$Te$_3$ and related alloys are referred to as Bi$_2$Te$_3$ chips.

2 Experimental design and procedure

Hot-pressed p- and n-type Bi$_2$Te$_3$ ingots were acquired from a commercial vendor. They are usually manufactured starting with bismuth antimony, selenium and tellurium shot of 99.999% purity. An alloying process converts the pure elements into compound of designed composition. Powdered alloys are extruded at a temperature between 400 and 500 °C [15]. They are then cut into 8mm × 8mm × 1 mm chips. The composition of n-type alloy is (Bi$_{0.95}$Sb$_{0.05}$)$_2$(Te$_{0.95}$Se$_{0.05}$)$_3$ and that of p-type alloy is (Bi$_{0.2}$Sb$_{0.8}$)$_2$Te$_3$. The room temperature figures of merit are up to 3.3 × 10$^{-3}$ K$^{-1}$ for p-type alloys and 2.85 × 10$^{-3}$ K$^{-1}$ for n-type alloys [15]. The coefficient of thermal expansion (CTE) of Bi$_2$Te$_3$ is 16.4 ppm/°C. The Bi$_2$Te$_3$ chips are thoroughly cleaned and baked at 120 °C for 30 min for dehydration.

Figure 2 portrays the structure of the barrier/bonding layers on Bi$_2$Te$_3$ chips with Ag as the electrode. The Ag electrode can be connected to the ceramic plate by soldering or other bonding means. The Ag layer is fabricated by an electroplating process. A thickness range of 10–20 μm is used. To search for bonding/barrier layers, we start with Pd because it has long been used in commercial TE cooling modules. Ni/Au, Ag, and Ti/Au are then studied. To produce a few microns of Pd, Ni/Au, and Ag layers, respectively, on Bi$_2$Te$_3$ chips, electroplating processes are employed. For depositing Ti films, we are not able to find a
plating solution. Thus, the Ti/Au layers are deposited by electron beam thermal evaporation in one vacuum cycle in 1 × 10^{-6} torr vacuum. The Ti layer is expected to bond to Bi$_2$Te$_3$ chips while the Au layer protects the Ti layer against oxidation.

The samples fabricated are cut in cross section and polished for examinations by optical microscope, scanning electron microscope (SEM) and EDX analysis. Some samples are annealed at 250 °C for 200 h prior to the cutting and polishing processes.

3 Experimental results and discussion

3.1 Pd barrier/bonding layer

The Bi$_2$Te$_3$ chips were coated with 1 μm Pd by electroplating process. Figure 3a and b show the SEM images of Pd surface on Bi$_2$Te$_3$ at low and high magnification, respectively. The surface of Pd is smooth and bonds well to Bi$_2$Te$_3$. The Pd grain size is less than 100 nm. The samples were then plated with 10 μm Ag and annealed at 250 °C for 10 h. After annealing, the Ag layer still adheres to the Pd layer which also bonds to the Bi$_2$Te$_3$ chip. To further study whether the Pd layer can sustain stresses induced by...
CTE mismatch while bonding on alumina substrate, the Bi$_2$Te$_3$/Pd/Ag samples were plated with a layer of 5 μm In and a thin Ag cap layer. The Bi$_2$Te$_3$ chips were bonded to alumina substrates. The bonded structure was cut in cross section and polished for evaluations. Figure 4a exhibits a cross section SEM image. It is observed that a gap exists between Pd and Bi$_2$Te$_3$. This is the breakage interface due to CTE mismatch between Bi$_2$Te$_3$ and alumina. The Ag layer on Bi$_2$Te$_3$ was well bonded to the Ag layer on the alumina substrate. On Fig. 4a, it is also found that Pd and Ag atoms have diffused into Bi$_2$Te$_3$ by as deep as 5 μm during the annealing process and prior to the bonding. Figure 4b and c display the EDX spectra at locations A and B marked on Fig. 4a. Table 1 provides quantitative EDX data. Location A is in a darker region on the back-scattered electron (BSE) image. The EDX system detects Bi, Te, Ag and Pd. Table 1 shows 54 at.% Ag and 5 at.% Pd. Significant Ag has diffused through Pd into Bi$_2$Te$_3$. This makes the Ag diffused region darker on the BSE image because Ag has a smaller atomic number than Bi and Te. The BSE image suggests that Ag has diffused to 5 μm in depth after annealing at 250 °C for 10 h. At location B, which is 7 μm away from the interface, 7 at.% Ag is detected. The small Ag amount does not make the region appear darker on the BSE image. As a result of Ag diffusion, Pd is not a good barrier layer on Bi$_2$Te$_3$ to block Ag.

### Table 1 EDX quantitative data at locations A and B marked in Fig. 4a

| Location | At.% |
|----------|------|
|          | Bi   | Te   | Pd | Ag  |
| A        | 8    | 31   | 5  | 54  |
| B        | 14   | 78   | 1  | 7   |

The accelerating voltage is 20 kV.

#### 3.2 Ni/Au barrier/bonding layers

Bi$_2$Te$_3$ chips were plated with 5 μm Ni, followed by 1 μm Au and 10 μm Ag. Au layer works as an adhesion layer between Ni and Ag. Figure 5a, b, c, and d display SEM images on the Au surface of Bi$_2$Te$_3$/Ni (5 μm)/Au (1 μm) and on the Ag surface of Bi$_2$Te$_3$/Ni (5 μm)/Au(1 μm)/Ag (10 μm) at low and high magnification, respectively. These images show that the surface of Au and Ag layers are flat and smooth. The surface roughness is less than 1 μm and the grain sizes of electroplated Au and Ag are both smaller than 50 nm. All the electroplated layers are well bonded to each other. Subsequently, the Bi$_2$Te$_3$/Ni/Au/Ag samples were annealed at 250 °C for 10 h. Figure 6 displays the cross section SEM image of Bi$_2$Te$_3$/Ni/(5 μm)/Au (2 μm)/Ag (10 μm) sample after annealing at 250 °C for 10 h. Severe inter-diffusions among Bi$_2$Te$_3$/Ni, Ni/Au and Ni/Au/Ag layers are observed. Table 2 presents EDX quantitative data at five locations, A, B, C, D, and E, marked on Fig. 6. The accelerating voltage is 20 keV. These EDX data show inter-diffusions between Bi$_2$Te$_3$ and Ag/Au/Ni. At location A, large amount of Ag and Au are detected in the original Ni layer, indicating that Ag and Cu atoms have diffused into the

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**Fig. 5** SEM images on the surfaces of Bi$_2$Te$_3$/Ni (5 μm)/Au (1 μm) at a low magnification and b high magnification, and of Bi$_2$Te$_3$/Ni (5 μm)/Au (1 μm)/Ag (10 μm) at c low magnification and d high magnification.
Ni layer during annealing. At locations B and C, which are right above and below the breaking interface, respectively, a large quantity of Ni and Te are detected as well as a small amount of Bi. This suggests that Ni and Bi$_2$Te$_3$ have inter-diffused, forming NiTe layer [16, 17]. Since the atomic ratio between Ni and Te is around 0.7 ~ 1:1, this layer is probably NiTe compound. Location D and E are basically Bi$_2$Te$_3$. The BSE image clearly shows that the breakage incurs inside the NiTe compound. Apparently, NiTe compound is weak and breaks due to stress induced by CTE mismatch in the multilayer structure. Thus, the Ni/Au composite is not a good choice for bonding/barrier layer.

3.3 Ag barrier/bonding layer

This is the simplest design because Ag itself is the electrode. In experiment, 10 µm Ag was electroplated on Bi$_2$Te$_3$ chips, followed by annealing at 250 °C for 10 h. Figure 7a and b show the surface of Ag layer on Bi$_2$Te$_3$ before annealing at low and high magnification, respectively. The Ag layer bonds well to Bi$_2$Te$_3$ and its grain size is less than 50 nm. Figure 8 exhibits the cross section SEM image a Bi$_2$Te$_3$/Ag (10 µm) sample after annealing. Severe inter-diffusion between Ag and Bi$_2$Te$_3$ is observed. An Ag$_2$Te compound layer is formed based on EDX analysis and Ag-Bi-Te phase diagram [18]. This layer has some voids and partly breaks off the Bi$_2$Te$_3$ chip. It is clear that Ag is not a good barrier/bonding layer for Bi$_2$Te$_3$.

3.4 Ti/Au barrier/bonding layers

Bi$_2$Te$_3$ were coated with 100 nm Ti and 100 nm Au by an E-beam thermal evaporator and then plated with 20 µm Ag. Figure 9a and b are the SEM images on Au surface of a Bi$_2$Te$_3$/Ti/Au sample at low and high magnification, respectively. The Ti (100 nm)/Au (100 nm) layers are well deposited on the Bi$_2$Te$_3$ chip with good uniformity. Figure 9c and d show the Ag surface of a Bi$_2$Te$_3$/Ti/Au/Ag sample at low and high magnification, respectively. The Ag morphology is different from the Ag plated on other barrier layers. The grains of Ag layer plated on Ti/Au are coarser. The grain size is about 100 nm. Without annealing, a few samples were cut and polished for examinations. Figure 10a and b display the cross section SEM images of a Bi$_2$Te$_3$/Ti/Au/Ag sample at low and high magnification, respectively. It is observed that the Ti layer bonds well Bi$_2$Te$_3$, the Au layer bonds well to the Ti layer and the Ag layer bonds well to the Au layer. Figure 10b also demonstrates that the Ti/Au

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**Table 2**

| Location | Bi | Te | Ni | Au | Ag |
|----------|----|----|----|----|----|
| A        | 4  | 2  | 13 | 39 | 42 |
| B        | 6  | 45 | 46 | 2  | 1  |
| C        | 7  | 52 | 38 | 1  | 1  |
| D        | 62 | 31 | 5  | 1  | 1  |
| E        | 54 | 42 | 2  | 1  | 1  |

The accelerating voltage is 20 kV.
layers have excellent step coverage over the rough Bi$_2$Te$_3$ surface. The Ti/Au layers cover all the steps, jags, and protuberances. Moreover, no Ag or Au atoms diffuse through the Ti layer and get into Bi$_2$Te$_3$. Also, no Bi$_2$Te$_3$ diffuses through the Ti layer and gets into the Ag layer either.

To further evaluate the barrier/bonding functions of Ti/Au layers, Bi$_2$Te$_3$ chips with Ti (100 nm)/Au (100 nm)/Ag (20 µm) were annealed at 250 °C for 50 h. Figure 11a and b exhibit the cross section SEM images of a sample after annealing at low and high magnification, respectively. These BSE images indicate that there is no interdiffusion among Ag, Ti/Au, and Bi$_2$Te$_3$ chips. In the Bi$_2$Te$_3$ region, no other element traces show up on the contrast of the image. This means that the integrity of Bi$_2$Te$_3$ chips is well preserved after the annealing. Moreover, the Ti/Au layers still maintain exceptional step coverage over the rough Bi$_2$Te$_3$ surface. They also adhere to the Ag electrode and

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**Fig. 8** SEM image on the cross section of Bi$_2$Te$_3$/Ag (10 µm) after annealing at 250 °C for 10 h. An Ag$_2$Te compound layer is formed between Bi$_2$Te$_3$ and Ag. It has some voids and partly breaks off the Bi$_2$Te$_3$ chip.

**Fig. 9** SEM images on the Au surfaces of Bi$_2$Te$_3$/Ti (100 nm)/Au (100 nm) at a low magnification and b high magnification, and on the Ag surfaces of Bi$_2$Te$_3$/Ti (100 nm)/Au (100 nm)/Ag (10 µm) at c low magnification and d high magnification.

**Fig. 10** Cross section SEM images of Bi$_2$Te$_3$/Ti (100 nm)/Au (100 nm)/Ag (20 µm) at a low magnification and b high magnification without annealing. The Ti/Au layers exhibit excellent step coverage on the rough Bi$_2$Te$_3$ surface. The Ti/Au layers are continuous and cover the entire Bi$_2$Te$_3$ surface with any breakage or pinhole.

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Fig. 8 SEM image on the cross section of Bi$_2$Te$_3$/Ag (10 µm) after annealing at 250 °C for 10 h. An Ag$_2$Te compound layer is formed between Bi$_2$Te$_3$ and Ag. It has some voids and partly breaks off the Bi$_2$Te$_3$ chip.

Fig. 9 SEM images on the Au surfaces of Bi$_2$Te$_3$/Ti (100 nm)/Au (100 nm) at a low magnification and b high magnification, and on the Ag surfaces of Bi$_2$Te$_3$/Ti (100 nm)/Au (100 nm)/Ag (10 µm) at c low magnification and d high magnification.

Fig. 10 Cross section SEM images of Bi$_2$Te$_3$/Ti (100 nm)/Au (100 nm)/Ag (20 µm) at a low magnification and b high magnification without annealing. The Ti/Au layers exhibit excellent step coverage on the rough Bi$_2$Te$_3$ surface. The Ti/Au layers are continuous and cover the entire Bi$_2$Te$_3$ surface with any breakage or pinhole.
the Bi$_2$Te$_3$ chip well. Next, the annealing time was extended to 200 h. Figure 12a exhibits the cross section SEM image of a sample which was annealed at 250 °C for 200 h: a high magnification and b low magnification. The thin Ti/Au layers show exceptional step coverage over the rough Bi$_2$Te$_3$ surface even after the annealing process. No Ag is detected in the Bi$_2$Te$_3$ chip

Fig. 12 SEM and EDX evaluation of a Bi$_2$Te$_3$/Ti (100 nm)/Au (100 nm)/Ag (20 μm) sample after annealing at 250 °C for 200 h. a Cross section SEM, b, c, d, and e EDX spectra at locations 5, 10, 20 and 100 μm below the Ti/Au interface with an accelerating voltage 20 keV. EDX quantitative data are provided in Table 3. Again, the Ti/Au layers still keep the excellent step coverage on the rough Bi$_2$Te$_3$ surface after the annealing process. No Ag is detected in the Bi$_2$Te$_3$ chip.
present the EDX spectra at an accelerating voltage 20 keV at the locations 5, 10, 20, and 100 μm away from the Ti/Au interface. The Sb, Te, and Bi peaks are clearly detected. Sb is there because this is a p-type material. The EDX data are provided in Table 3. At all four locations, the compositions of Sb, Te, and Bi are 30 ~ 34 at.%, 52 ~ 54 at.%, and 8 ~ 10 at.%, respectively. On the EDX spectra, Ag peak is barely seen. The 1 ~ 2 at.% Ag shown in Table 3 is within the error bar of the EDX system. It is thus clear that no Ag atoms diffuse through Ti/Au layers and get into Bi₂Te₃. The Ti/Au layers still work functionally as barrier and adhesion layers. Ti/Au themselves do not diffuse and spread outwards into Ag and Bi₂Te₃ region.

The results presented above illustrate that Ti/Au layers meet the four requirements of barrier/bonding composite design even after annealing at 250 °C for 200 h: (a) prevent Ag and Bi₂Te₃ from inter-diffusion, (b) bond well to Ag, (c) bond well to Bi₂Te₃, and (d) do not themselves diffuse into Bi₂Te₃ and Ag.

4 Summary

We have demonstrated that Ti (100 nm)/Au (100 nm) layers deposited on Bi₂Te₃ chips by E-beam thermal evaporation performs well as bonding/barrier composite between Bi₂Te₃ chips and Ag electrode. After annealing at 250 °C for 200 h, there is no sign of inter-diffusion between Bi₂Te₃ chips and Ag electrode. The Ti/Au layers still bond well to Bi₂Te₃ on one side and Ag on the other. The Ti/Au atoms themselves do not diffuse into Bi₂Te₃ either. Furthermore, the Ti/Au layers provide excellent step coverage on the Bi₂Te₃ surface with a few microns of surface roughness. The coverage is continuous and complete.

Other bonding/barrier composite designs that were experimented with include Pd, Ni/Au, and Ag, respectively. After annealing at 250 °C for 10 h, they diffuse into Bi₂Te₃ to produce alloys or form compounds. The resulting compounds are usually weak and break more easily than other layers in the structure.

Table 3 EDX quantitative data of a Bi₂Te₃/Ti (100 nm)/Au (100 nm)/Ag (10 μm) sample at locations in Bi₂Te₃ at depth 5, 10, 20, and 100 μm, respectively, from the Ti/Au interface

| Location | Sb | Te | Bi | Ag |
|----------|----|----|----|----|
| d = 5 μm | 31 | 54 | 9  | 1  |
| d = 10 μm| 34 | 52 | 9  | 1  |
| d = 20 μm| 30 | 54 | 10 | 2  |
| d = 100 μm| 32 | 54 | 9  | 1  |

The sample was annealed at 250 °C for 200 h. The accelerating voltage is 20 keV.

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References

1. R.R. Heikes, R.W. Ure, Thermoelectricity: Science and Engineering (Interscience, New York, 1961)
2. F.D. Ross, Thermoelectricity and thermoelectric power generation. Solid-State Electron 11, 833–848 (1968)
3. C. Wood, Materials for thermoelectric energy-conservation. Rep. Prog. Phys. 51, 459–539 (1988)
4. G. Jeffrey Snyder, E.S. Toberer, Complex thermoelectric materials. Nat. Mater. 7, 105–114 (2008)
5. D.M. Rowe, Thermoelectrics Handbook: Macro to Nano (Taylor and Francis Group, New York, 2006), pp. 1–9. ISBN 0849322642
6. E.J. Winder, A.B. Ellis, Thermoelectric devices: solid-state refrigerators and electrical generators in the classroom. J. Chem. Educ. 73, 940–946 (1996)
7. http://www.inbthermoelectric.com/highperformance.html
8. C.B. Satterthwaite, Electrical and thermal properties of Bi₂Te₃. Phys. Rev. 108, 1164–1170 (1957)
9. B.W. Howlett, S. Misra, M.B. Bever, Trans. AIME 230, 1361–1367 (1964)
10. N.Kh. Abrikosov, V.F. Bankina, Kharitonovich, Semiconductor Compound and its Properties (Nauka, Moscow, 1967)
11. Y.C. Lan, D.Z. Wang, G. Chen, Z.F. Ren, Diffusion of nickel and tin in p-type (Bi, Sb)₂Te₃ and n-type Bi₂(Te, Se)₃ thermoelectric materials. Appl. Phys. Lett. 92, 101910 (2008)
12. T. Kacisich, E. Kolawa, J.P. Fleirual, T. caillat, M.-A. Nicolet, Films of Ni-7%, Pd, Pt and Ta-Si-N as diffusion barriers for copper on Bi₂Te₃. J. Phys. D Appl. Phys. 31, 2406–2411 (1998)
13. O.D. Lyore, T.H. Lee, R.P. Gupta, J.B. White, H.N. Alshareef, M.J. Kim, B.E. Gnade, Interface characterization of nickel contacts to bulk bismuth tellurium selenide. Surf. Interface Anal. 31, 440–444 (2008)
14. W.P. Lin, P.J. Wang, C.C. Lin. Bonding/barrier layers on bismuth telluride (Bi₂Te₃) for high temperature applications, 60th Electron. Compon. Technol. Conf., pp 447–450 (2010)
15. D. Vassilevskiy, N. Kukhar, S. Turenne, R.A. Masut 2007 “Hot extruded (Bi,Sb)₂(Te,Se)₃ alloys for advanced thermoelectric modules”. Oral presentation, 5th European Conference on Thermoelectrics
16. K. Xiong, W. Wang, H.N. Alshareef, R.P. Gupta, J.B. White, B.E. Gnade, K. Cho, Electronic structures and stability of Ni/Bi₂Te₃ and Cu/Bi₂Te₃ interfaces. J. Phys. D Appl. Phys. 43, 115303 (2010)
17. R.P. Gupta, O.D. Iyore, K. Xiong, J.B. White, K. Cho, H.N. Alshareef, B.E. Gnade, Interface characterization of cobalt contacts on bismuth selenium telluride for thermoelectric devices. Electrochem. Solid-state Lett. 12, H395–H397 (2009)
18. R. Schmid Fetzer 1988 Ag-Bi-Te phase diagram, ASM Int. (http://www1.asminternational.org/asmenterprise/APD/ViewAPD.aspx?id=950339)