Effect of aluminum content on the structural, morphology, and electrical properties of Al$_{1-x}$Sb$_x$ thin films

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Abstract: Bulk Al$_x$Sb$_{1-x}$ samples were prepared with different x ratios (0.1, 0.3, 0.5, 0.7, and 0.9) by quenching technique. This was done by mixing the aluminum and antimony elements according to the proper atomic weight and putting them in an evacuated quartz ampoule which then sealed and heated at 1273 K for five hours and left to cool in air. Thin films of Al$_x$Sb$_{1-x}$ were prepared by using thermal evaporation under vacuum of 10$^{-5}$ mbar on glass substrates at room temperature with deposition rate (10$^{-15}$nm/min) at thickness of ~500nm. The structures of Al$_x$Sb$_{1-x}$ bulk and thin films have been studied by X-ray diffraction technique. The results showed that all alloys have polycrystalline structures and the peaks at composition ratio x=0.3, 0.5 and 0.7 were identical with the AlSb standard peaks while at x=0.1 and 0.9 the peaks are identical with Sb and Al respectively. The x-ray pattern of the prepared thin films are polycrystalline and the peaks identical with cubic structure also the peaks intensity decrease with the increase of aluminum ratio in the prepared thin films. AFM measurements showed the non-regular variation (increasing and decreasing) of both the average grain size and average surface roughness with the increasing of composition ratio. Al$_x$Sb$_{1-x}$ thin films showed high charge carrier concentration $n_H$ especially at x=0.1 and 0.3 on the other side charge carrier concentration showed reduction with the increase of aluminum content whereas $n_H$ reach minimum value at x=0.7 and then increases with further increase of aluminum content. The electrical conductivity of Al$_x$Sb$_{1-x}$ declare similar behavior where it reach minimum value at x=0.5. From another side Al$_x$Sb$_{1-x}$ thin films show high conductivity resemble that of metallic material especially also at x=0.1 and 0.3.

1. Introduction

AlSb is an environment-friendly material with the reserves of both Al and Sb being very rich in the Earth. AlSb is considered as one of the most promising materials for photovoltaic applications[1]. AlSb semiconductors are good candidates for high speed, low power consumption electronic devices and hence these properties are very important in digital analogical systems for data processing, communication, imaging, and sensing, especially in portable equipment and satellites [2]. Crystalline films can be prepared by many methods such as molecular beam epitaxy (MBE) magnetron sputtering [3-4]. The characteristics of sputtered thin films depend strongly upon the deposition conditions such as temperature, pressure, substrate, growing rate and other parameters [5-8]. There is a few works interested with the fabrication of aluminum antimonide films by thermal evaporation, in particular regarding AlSb thin films [9-11]. The electrical properties of AlSb films are very promising and could be beneficial if better exploited. AlSb has the highest bandgap among the
antimonides (~1.63 eV), therefore is suitable for applications in solar cells. The XRD analysis AlSb thin films revealed that the films are polycrystalline of zinc-blende structure with peaks at \(2\Theta = 25:03^\circ, 41.61^\circ, 49.21^\circ\) corresponding to (111), (220), and (311) orientations, respectively. In both the two films the (111) peaks are the most intense peaks which imply that the crystals grow up preferentially along the (111) plane. This work concerned on the investigate role of aluminum content on the structural morphology and electrical parameters like activation energy, concentration of charge carriers, type of conductance and mobility.

2. Experimental Details

The starting material was synthesized by mixing appropriate quantity of high-purity (99.999\%) aluminum and antimonite and powder in different atomic ratio (0.1:0.9, 0.3:0.7, 0.5:0.5, 0.7:0.3, and 0.9:0.1). The mixture was sealed in an evacuated quartz tube and heated at 1272 K for 5 h. Al\(_x\)Sb\(_{1-x}\) films have been deposited by thermal evaporation technique under vacuum of about 10-5torr. The substrate to source distance was kept 15 cm. The samples were prepare at constant thickness of \(\approx 300\)nm. The thickness of the films was measured using Fizeau fringes method. The film thickness \(t\) [13] is given by

\[
    t = \frac{\lambda \Delta x}{2 \cdot x}
\]

Where \(\Delta x\) is the shift between the interference fringes, \(x\) is the distance between the interference fringes and \(\lambda\) is the He: Ne wavelength (589.3 nm). The deposition rate was maintained 10-20 \(\)Å/sec throughout sample preparation. Before evaporation, the glass substrates were subjected to several cleaning steps using isopropyl alcohol and distilled water. X – Ray diffractogram (Rigaku Miniflex, Japan) were obtained of these samples to get the structural information and to identify the film structure qualitatively. The scanning angle \(2\Theta\) range was from 20-80 (CuK\(\alpha\) line). To study the electrical properties for the films Ohmic contacts for the prepared films are produced by evaporating (Al) electrodes of 300 nm thickness, by means of thermal evaporation methods. Then the d.c conductivity (\(\sigma\)) has been studied using the electrical circuit which is consists of oven type Herease and Keithley (616).

3. Results and discussion

Figure 1 shows the X-ray diffraction patterns for bulk Al\(_x\)Sb\(_{1-x}\) at different aluminum content \((x = 0.1, 0.3, 0.5, 0.7\) and 0.9\). Table 1 shows a comparison between the experimental and the standard peaks from International Centre for Diffraction Data (JCPDS) for AlSb, Sb and Al system and their Miller indices.

It shows that all peaks of corresponding to the \(x = 0.1\) of Aluminum content are identically with the Sb standard peaks, while the residual \(x\) values (0.3, 0.5, 0.7 and 0.9) the peaks are identically with AlSb, Sb and Al respectively. These results are in agreement with many previous researches. The diffraction pattern revealed that the preferred plane for crystal growth alter with variation of aluminum content in the Al\(_x\)Sb\(_{1-x}\) binary system, on the other hand the addition peaks corresponded to Al will be appear as the aluminum content increase in the Al\(_x\)Sb\(_{1-x}\) binary system. It is obvious that the location of diffraction peaks suffered little shift to lower value at \(x = 0.5\) especially the diffraction peaks belonged to AlSb system, also the number of diffraction peaks corresponding to the AlSb system increases and be dominated upon other peaks at with increase of aluminum content at \(x = 0.5\) and 0.7. The diffraction peaks belonged to Sb become predominant at \(x=0.9\) indicated that some composition shift take place at high value of antimony.
Figure 1. XRD of Al$_x$Sb$_{1-x}$ Powders.

Table 1. X-ray diffraction data for bulk Al$_x$Sb$_{1-x}$ with different compositions.

| X  | 20 (Deg.) | FWHM (Deg.) | d$_{hkl}$ Exp.(Å) | C.C (nm) | hkl | d$_{hkl}$ Std.(Å) | Phase | card No.  |
|----|-----------|-------------|-------------------|----------|-----|------------------|-------|----------|
| 0.1| 28.6229   | 0.1941      | 3.1162            | 42.3     | (102)| 3.1113           | Hex. Sb | 96-500-0215 |
|    | 40.0185   | 0.2772      | 2.2512            | 30.5     | (104)| 2.2490           | Hex. Sb | 96-500-0215 |
|    | 41.9039   | 0.2495      | 2.1542            | 34.1     | (110)| 2.1542           | Hex. Sb | 96-500-0215 |
|    | 47.0055   | 0.1941      | 1.9316            | 44.7     | (105)| 1.9298           | Hex. Sb | 96-500-0215 |
|    | 48.4196   | 0.2773      | 1.8784            | 31.4     | (006)| 1.8790           | Hex. Sb | 96-500-0215 |
|    | 28.7061   | 0.1664      | 3.1074            | 49.3     | (102)| 3.1113           | Hex. Sb | 96-500-0215 |
|    | 29.1497   | 0.1386      | 3.0611            | 59.3     | (200)| 3.0673           | Cub. AlSb| 96-900-8833 |
|    | 40.1017   | 0.2772      | 2.2467            | 30.5     | (104)| 2.2490           | Hex. Sb | 96-500-0215 |
| 0.3| 41.6543   | 0.1663      | 2.1665            | 51.1     | (220)| 2.1689           | Cub. AlSb| 96-900-8833 |
|    | 41.9871   | 0.2218      | 2.1501            | 38.4     | (110)| 3.1542           | Hex. Sb | 96-500-0216 |
|    | 49.2514   | 0.1941      | 1.8486            | 45.0     | (311)| 1.8497           | Cub. AlSb| 96-900-8833 |
|    | 51.6359   | 0.2772      | 1.7687            | 31.8     | (202)| 1.7711           | Hex. Sb | 96-500-0215 |
|    | 66.4418   | 0.2219      | 1.4060            | 42.8     | (331)| 1.4074           | Cub. AlSb| 96-900-8833 |
| 0.5| 25.2680   | 0.1664      | 3.5218            | 49.0     | (111)| 3.5419           | Cub. AlSb| 96-900-8833 |
The presence of many number of peaks indicates that the films are polycrystalline in nature. These results are well in agreement with the reported values from the previous results[14], the strongest peak for the grown films at x= 0.3, 0.5 and 0.7 in Figure 2 occurred at 2θ=25.26° and at 2θ=48.92° which corresponds to (111) and (311) plane. The value of the lattice parameters obtained from the analysis of x-ray diffraction pattern are shown in Table 2. In films with x= 0.3, 0.5, and 0.7 the (111) peak is the most intense peaks which imply that the crystals grow up preferentially along the this direction. It is obvious that when aluminum contents increases the (111) peak intensity increases pronouncedly but then return to fall drastically for Al$_x$Sb$_{1-x}$ thin films with high aluminum content i.e. x=0.9, and the structure approach from amorphous or semi crystalline pronouncedly. No diffraction peak corresponding to metallic Al, Sb or other compound was observed.

| 28.8447 | 0.2218 | 3.0927 | 37.0 (102) | 3.1113 | Hex. Sb | 96-500-0215 |
| 29.2329 | 0.1387 | 3.0525 | 59.2 (200) | 3.0673 | Cub. AlSb | 96-900-8833 |
| 41.5553 | 0.2773 | 2.1916 | 30.6 (220) | 2.1689 | Cub. AlSb | 96-900-8833 |
| 41.7375 | 0.2218 | 2.1624 | 38.3 (110) | 3.1542 | Hex. Sb | 96-500-0216 |
| 49.3623 | 0.1941 | 1.8447 | 45.1 (311) | 1.8497 | Cub. AlSb | 96-900-8833 |
| 51.6913 | 0.2218 | 1.7670 | 39.8 (202) | 1.7711 | Hex. Sb | 96-500-0215 |
| 60.4251 | 0.2218 | 1.5308 | 41.5 (400) | 1.5337 | Cub. AlSb | 96-900-8833 |
| 66.4972 | 0.2218 | 1.4050 | 42.8 (331) | 1.4074 | Cub. AlSb | 96-900-8833 |
| 28.7338 | 0.1941 | 3.1044 | 42.3 (102) | 3.1113 | Hex. Sb | 96-500-0215 |
| 29.1220 | 0.1664 | 3.0639 | 49.3 (200) | 3.0673 | Cub. AlSb | 96-900-8833 |
| 38.5213 | 0.2772 | 2.3352 | 30.4 (111) | 2.3380 | Cub. Al | 96-900-8461 |
| 41.6543 | 0.1941 | 2.1665 | 43.8 (220) | 2.1689 | Cub. AlSb | 96-900-8833 |
| 49.2514 | 0.1941 | 1.8486 | 45.0 (311) | 1.8497 | Cub. AlSb | 96-900-8833 |
| 51.5804 | 0.1386 | 1.7705 | 63.7 (222) | 1.7709 | Cub. AlSb | 96-900-8833 |
| 60.3420 | 0.1386 | 1.5327 | 66.3 (400) | 1.5337 | Cub. AlSb | 96-900-8833 |
| 66.4140 | 0.1663 | 1.4065 | 57.1 (331) | 1.4074 | Cub. AlSb | 96-900-8833 |
| 29.1278 | 0.1941 | 3.0633 | 42.3 (200) | 3.0673 | Cub. AlSb | 96-900-8833 |
| 38.4658 | 0.1940 | 2.3384 | 43.4 (111) | 2.3380 | Cub. Al | 96-900-8461 |
| 40.0462 | 0.2496 | 2.2497 | 33.9 (104) | 2.2490 | Hex. Sb | 96-500-0215 |
| 41.9316 | 0.2218 | 2.1528 | 38.4 (110) | 2.1542 | Hex. Sb | 96-500-0215 |
| 44.7043 | 0.1941 | 2.0525 | 44.3 (200) | 2.0248 | Cub. Al | 96-900-8461 |
| 47.0333 | 0.2495 | 1.9305 | 34.7 (105) | 1.9298 | Hex. Sb | 96-500-0215 |
Figure 2. XRD of Al$_x$Sb$_{1-x}$ Thin Films deposited at room temperature with different composition.
Table 2. X-ray diffraction data for Al$_x$Sb$_{1-x}$ thin films with different compositions.

| x  | $2\theta$ (Deg.) | FWHM (Deg.) | $d_{hkl}$ Exp.(Å) | G.C (nm) | hkl | $d_{hkl}$ Std.(Å) | Phase | card No. |
|----|------------------|-------------|-------------------|----------|-----|------------------|-------|---------|
| 0.1 | 25.6506          | 0.3720      | 3.4701            | 21.9     | (111) | 3.5419           | Cub. AlSb | 96-900-8833 |
|   | 29.1450          | 0.3733      | 3.0615            | 22.0     | (200) | 3.0673           | Cub. AlSb | 96-900-8833 |
|   | 40.5948          | 0.3734      | 2.2206            | 22.7     | (104) | 2.2490           | Hex. Sb  | 96-500-0215 |
|   | 42.4535          | 0.2974      | 2.1275            | 28.7     | (220) | 2.1689           | Cub. AlSb | 96-900-8833 |
|   | 48.9219          | 0.2980      | 1.8603            | 29.3     | (311) | 1.8497           | Cub. AlSb | 96-900-8833 |
| 0.3 | 52.1190          | 0.4461      | 1.7535            | 19.8     | (222) | 1.7709           | Cub. AlSb | 96-900-8833 |
|   | 63.3457          | 0.3718      | 1.4670            | 25.1     | (400) | 1.5337           | Cub. AlSb | 96-900-8833 |
|   | 75.8364          | 0.5204      | 1.2535            | 19.4     | (242) | 1.2522           | Cub. AlSb | 96-900-8833 |
|   | 24.1635          | 0.2231      | 3.6802            | 36.4     | (300) | 3.7580           | Hex. Sb  | 96-500-0215 |
| 0.5 | 48.8476          | 0.2980      | 1.8630            | 29.3     | (311) | 1.8497           | Cub. AlSb | 96-900-8833 |
|   | 76.2825          | 0.2230      | 1.2472            | 45.3     | (242) | 1.2522           | Cub. AlSb | 96-900-8833 |
|   | 24.1634          | 0.2222      | 3.6803            | 36.6     | (300) | 3.7580           | Hex. Sb  | 96-500-0215 |
| 0.7 | 48.8476          | 0.3717      | 1.8630            | 23.5     | (311) | 1.8497           | Cub. AlSb | 96-900-8833 |
|   | 76.1338          | 0.4461      | 1.2493            | 22.6     | (242) | 1.2522           | Cub. AlSb | 96-900-8833 |
|   | 24.0892          | 0.2211      | 3.6914            | 36.8     | (300) | 3.7580           | Hex. Sb  | 96-500-0215 |
| 0.9 | 48.7732          | 0.5204      | 1.8656            | 16.8     | (311) | 1.8497           | Cub. AlSb | 96-900-8833 |
|   | 76.2082          | 0.4461      | 1.2483            | 22.6     | (242) | 1.2522           | Cub. AlSb | 96-900-8833 |
|   | 24.1631          | 0.3711      | 3.6803            | 21.9     | (300) | 3.7580           | Hex. Sb  | 96-500-0215 |
| 3.1 Atomic Force Microscopy Analysis (AFM)

The grain size (grain diameter) and average roughness of Al$_x$Sb$_{1-x}$ thin films prepared by thermal evaporation with different composition (x=0.1 , 0.3 , 0.5 , 0.7 and 0.9) prepared at room temperature have been measured using AFM. Figure 3 declared the AFM images of Al$_x$Sb$_{1-x}$ thin films with different x values. It is obvious from table 3 that the average grain size get to decreases with increasing of aluminum content up x=0.5 and then increases reach maximum value and the return to decrease at high x value. while the roughness get to change in non systematic sequence i.e. decreases and increases with the increase of aluminum content in the Al$_x$Sb$_{1-x}$ system. Indeed the grain size decreases from 93.17 to 84.03 nm when x increases from 0.1 to 0.5 and then increases to maximum value 93.79 nm and eventually fall to 73.03 nm while roughness in general changed from 0.958 to 0.596 nm with the increase of x content from 0.1 to 0.9. These results give indication that continuous addition of aluminum to the hast material Sb reduced the degree of crystallinity and this will reflect of the hole properties of the prepared thin films.
Figure 3. AFM images for Al$_{x}$Sb$_{1-x}$ thin films prepared at room temperature with thickness 300nm by thermal evaporation with different composition ($x$=0.1 , 0.3 , 0.5 , 0.7 and 0.9) .
The type of charge carriers, concentration \( n_i \) and Hall mobility \( \mu_i \), have been estimated from Hall measurements. Table 4 illustrates the main parameters estimated from Hall effect measurements for Al\(_x\)Sb\(_{1-x}\) thin films with different aluminum concentration deposited at room temperature. It is clear from this table that all the samples declared a positive Hall coefficient (p-type charge carriers), i.e. Hall voltage increases with the increasing of the current, except thin films of Al\(_x\)Sb\(_{1-x}\) at \( x = 0.5 \) declared negative a negative Hall coefficient (n-type) i.e. Hall voltage decreasing with the increasing of the current. The carriers concentration exhibit to change randomly with the variation of Al content. The carrier concentration decreases with the increase of Al concentration to reach minimum value at

| \( x \) | Average roughness (nm) | Average grain size (nm) |
|-------|------------------------|------------------------|
| 0.1   | 0.958                  | 93.17                  |
| 0.3   | 0.774                  | 89.36                  |
| 0.5   | 1.11                   | 84.03                  |
| 0.7   | 1.02                   | 93.97                  |
| 0.9   | 0.596                  | 73.03                  |

### 3.2 The Electrical Properties

The electrical property of Al\(_x\)Sb\(_{1-x}\) thin film is an important aspect of the solar cells performance. For the polycrystalline semiconductor films, the dark conductivity can be presented as[15]

\[
\sigma = \sigma_0 \exp \left( \frac{-E_a}{kT} \right) \exp \left( \frac{-E_b}{kT} \right) \quad \text{………………(3)}
\]

where \( E_a \) is conductivity activation energy where \( E_a = E_f + E_b, \) \( E_f \) is Fermi energy, \( E_b \) is activation energy of carrier mobility and \( \exp(-E_b/kT) \) describes the temperature dependence of carrier mobility. Hence, \( E_b \) is just the average boundary barrier. Figure 4 shows the \( \ln(\sigma) \) versus \( 1000/T \) curves of AlSb thin films which were deposited with various composition ratios. The \( \sigma \) and \( E_a \) for Al\(_x\)Sb\(_{1-x}\) thin films with various aluminum content were calculated from Eq. (3) and the results are shown in Figure 4. It is evident that the conductivity increases with increase of temperature. It is indicate the semiconducting behavior of Al\(_x\)Sb\(_{1-x}\) thin films at the used temperature range. It is obvious that the number of mechanism of conduction take place in the used temperature range depends on the aluminum content in the prepared thin films. The conductivity mechanisms can be classified as:

1. transport by excited carrier to the extended state near the conduction or valance bands which yield the activation energy \( E_a \) in the high temperature range.
2. transport by carriers excited into localized states at the edges of the valence or conduction bands which yield the low activation energy \( E_a \) in the low temperature range.
3. hopping transport by carriers with energies near the Fermi level. It is clear that the conductivity take place through two mechanisms for \( x \) content, while for moderate \( x \) value i.e. when \( x = 0.5 \) and 0.7 there is one conductivity mechanism, but for high aluminum content i.e. \( x \geq 0.7 \). the conductivity take place through three mechanisms, and hence there are three activation energy. This behavior related to increase and decrease of crystal size with the addition of aluminum to the antimony as shown from x-ray diffraction.

The estimated activation energies values are listed in Table 4. It is clear from this table that the activation energies exhibit to change in non regular manner with the increase of \( x \) value i.e. decreased and increased with the increase of Al content. The reduction of activation energy \( E_a \) with the increase of Al content is resulting from structural enhancement (increasing of crystal size) which giving rise to reduction of energy gap which in turn reduces the energy requires to transport the carriers from Fermi level to the conduction band. The compensation of defects and tail stated when \( x = 0.5 \) and 0.7 responsible about the appearance of one conductivity mechanism while the addition of more aluminum created more and more voids and defects which approach structure from amorphous and increase of activation energy.
x= 0.5 and then return to increase with further addition of Al. This result is related to the reduction of crystal size (reduction degree of crystallinity) which giving rise to more localized states in the band gap. While the decreasing of the trapping centers in band gap which responsible about the reduction of the number of charge carriers and their mobility at x= 0.5 as a result of red shift the band gap [16]. The increasing of charge carriers and mobility are responsible about the increase of conductivity as the Al content increased. It is obvious that the conductivities at x=0. 1, 0. 3 resemble that of metallic material, since they lie out of the semiconductor conductivity range \((10^8 - 10^3)(\text{ohm.cm})^{-1}\), except at x=0.5 and 0.7 the conductivity is in the mentioned range. Hall mobility \(\mu_H\) show non systematic variation with x content , but in general \(\mu_H\) increases with increasing of aluminum content . Table 5 illustrates the values of charge concentration \(n_H\), Hall mobility \(\mu_H\) and the type of charge carriers for \(\text{Al}_x\text{Sb}_{1-x}\) thin films with different compositions.

\[\text{Figure 4. The ln(\sigma) versus } 1=T \text{ curves of AlSb thin films which were deposited with various composition ratios}\]

| Table 4. D.C parameters for \(\text{Al}_x\text{Sb}_{1-x}\) thin films with different compositions |
|---|---|---|---|---|---|
| x  | \(E_a_1\) (eV) | Temp. Range (K) | \(E_a_2\) (eV) | Temp.Range (K) | \(E_a_1\) (eV) | Temp. Range (K) | \(\sigma_{RT}\) (\(\Omega\cdot\text{cm}\))^{-1} |
|----|---|---|---|---|---|---|---|
| 0.1 | - | - | 0.0576 | 293-383 | 0.0349 | 383-473 | 4.88E+01 |
| 0.3 | - | - | 0.0160 | 293-383 | 0.0268 | 383-473 | 9.36E+02 |
| 0.5 | - | - | - | - | 0.0507 | 293-473 | 3.85E+02 |
| 0.7 | - | - | - | - | 0.0135 | 293-473 | 9.11E+02 |
| 0.9 | 0.0135 | 293-443 | 0.2047 | 293-443 | 0.3982 | 443-473 | 2.24E+01 |

| Table 5. Hall Effect parameters for \(\text{Al}_x\text{Sb}_{1-x}\) thin films with different compositions |
|---|---|---|---|---|
| x  | \(\sigma_{RT}\) (\(\Omega\cdot\text{cm}\))^{-1} | \(n_H\) (cm^{-3}) | \(R_H\) (cm^{2}/V.sec) | \(\mu_H\) (cm^{2}/V.sec) | type |
|----|---|---|---|---|---|
| 0.1 | 2.377x10^4 | 1.509x10^{20} | 4.135x10^{-2} | 983.1 | p |
| 0.3 | 8.944x10^3 | 6.690x10^{20} | 9.328x10^{3} | 83.43 | p |
| 0.5 | 1.977x10^5 | -1.724x10^{12} | -3.621x10^{6} | 71.60 | n |
| 0.7 | 2.095x10^5 | 1.192x10^{12} | 5.236x10^{6} | 109.7 | p |
| 0.9 | 8.792 | 1.607x10^{16} | 3.883x10^{2} | 3414 | p |
4. Conclusions
1- The prepared Al$_x$Sb$_{1-x}$ alloys with different compositions as well as deposited thin deposited at room temperature have polycrystalline with cubic structure.
2- The increase of aluminum has significant effect on the plane of crystal growth and structure of the alloys and the prepared thin films
3- The gain size and roughness of Al$_x$Sb$_{1-x}$ thin films sample changed in non regular manner with the increasing of aluminum content.
4- Minimum conductivity, charge concentration occur at x=0.5.
5- Al$_x$Sb$_{1-x}$ thin films declare metallic conductivity at x=0.1 0.3 and 0.9.
6- All Al$_x$Sb$_{1-x}$ thin films are p-type semiconductors while Al$_{0.5}$Sb$_{0.5}$ is n type.
7- The Al$_{0.5}$Sb$_{0.5}$ has been chosen as one of the most promising materials for photovoltaic applications.

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