EFFECT OF INDIUM ADDITION ON PHYSICAL AND MECHANICAL PROPERTIES OF AL-SB ALLOYS RAPIDLY SOLIDIFIED FROM MELT

KAREEM. T. ABUL-NASR^{1,*}, A. RAOUF. MOHAMED², RIZK MOSTAFA SHALABY³ & MUSTAFA KAMAL⁴

^{1,2}Physics Department, Faculty of Science, Port Said University, Port Said, Egypt

^{3,4}Metal Physics Laboratory, Physics Department, Faculty of Science, Mansoura University, Mansoura, Egypt

ABSTRACT

Aluminum antimony indium (AlSbIn) with a face-centered Cubic type structure is a promising semiconductor alloy. In this work, $Al_{90-x}Sb_xIn_{10}$ (where $x=10$ and 20 wt %) alloys were prepared by melt-spinning technique. The influence of Indium co replacement on the structure, microstructure, tensile stress, conductivity, Vickers hardness and activation energy of $Al_{90}Sb_{10}$ and $Al_{80}Sb_{20}$ were investigated by the X-ray diffraction (XRD), the scanning electron microscopy (SEM), the tensile test machine (TS), the electrical resistivity, the microhardness technique and the differential scanning calorimetry (DSC). The mechanical measurement shows that the Yield strength of the $Al_{80}Sb_{10}In_{10}$ and $Al_{70}Sb_{20}In_{10}$ modified alloy in sequence decreased 28% and 9% relative to the unmodified alloy and the change in hardness occurs that is credited to changes in the microstructure. The results reveal that the InSb-containing alloys have better transport properties with inferior scattering time (relaxation time) due to short of the electron mean free path and intermetallic compounds AlSb with InSb particle hardening. We are suggesting the practicability of using $Al_{70}Sb_{20}In_{10}$ in designing a junction useable in the multijunction solar cell.

KEYWORDS: Ternary AlSbIn Melt-Spun Process –Aluminum Indium Antimonide $Al_{0.5}In_{0.5}Sb$ (IMC) – Eutectic Phase – Micro Creep Indentation & Valance Electron Concentration (VEC)

Received: Jun 09, 2020; Accepted: Jun 29, 2020; Published: Sep 21, 2020; Paper Id.: IJMPERDJUN20201371

1. INTRODUCTION

Aluminum is the most popular nonferrous metal and is very commonly employed by its abundant resource capacity, lightweight, good mechanical properties, suitable corrosion resistance, and excellent power conductivities in many areas, including packaging, building transportation, and electric materials. A preferred method for increasing the strength and plasticity of metallic materials is grain refining that is achieved through changing the grain structure by different methods. Multijunction III-V cells have higher performance than rival technologies, but due to existing production techniques and materials, these solar cells cost considerably more money. The focus of active research is therefore on reducing the electricity costs created by these solar cells through the development of new substrates, absorber materials, and manufacturing techniques; increased efficiency and expanding the multi-connected concept to other photovoltaic (PV) technologies[4, 11, 37]. While III-V alloys and materials are much more complicated in manufacturing plants on a large scale, it is useful and even necessary to create devices from such materials for some applications[14, 20]. Instead of mechanical properties, semiconductor alloys are designed to optimize optical and electronic properties, as in most electronics alloys. Semiconductor alloys are usually less mobile because of the scattering of the alloy. Multi-junction devices use a high bandgap top cell to absorb photons with high-energy properties and permit the photons with low energy to transfer. Underneath the high band gap junction is a medium

of the slightly lower bandgap for photons to consume a little less energy (longer wavelengths)[9, 10, 39]. Typical multijunction cells use two or more absorbing joints, and with the number of joints, the theoretical potential efficiency increases. Schwarz and Koch [36] considered that the amorphous reaction in as-milled powders was similar to the amorphization happening through the isothermal annealing of crystalline metallic thin films. The intense deformation accelerates interdiffusion, and the significant dislocations densities increase the free energies of both pure components and intermetallic compounds, but therefore a melt-spun technique improves it. The Indium additive role on refining the grain boundaries by decreasing the dendrite arm spacing. That has been done by adding five wt.% indium mainly, which may be attributed to the rapid increasing hardness[45]. The chill-block melt spinning technique is an effective way to produce rapid solidification with a high cooling capacity rate, which is more suitable for industrial applications and strongly supports the configuration of metastable crystalline and amorphous phases [15, 17]. In the present work, samples at different Sb concentrations have been constructed and In additive with ten wt% to study the particle sizes, enthalpy, and some other thermal properties. The embeddability mechanism of the samples' surface structure was investigated via analyzing SEM images. This study will provide a useful piece of information, AlSb, AlSbIn, and InSb IMC forming effects on the microstructure, electrical, and thermal properties.

2. MATERIALS AND METHODS

Two samples of different compositions prepared from Al, Sb, and In of purity greater than 99.99% ($\text{Al}_{90-x}\text{-Sb}_x\text{-In}_{10}$ (where $x=10$ and 20)), and it prepared in the metal physics laboratory, physics department, faculty of science, Mansoura University. The raw materials were put in a porcelain crucible and melted by an electric furnace at 850°C for 25 min. It is minutely agitated to increase the homogenization by using a stirring graphite rod. The melt spinning technique used to prepare samples in ribbons by using a high cooling rate of approx. 3.7×10^5 K/s [17]. The suitable form for the mensuration prepared using blade cutter. The microstructure characterization explored by the X-ray diffraction (XRD) analysis has been done using a PANalytical 3 kW X'pert Powder XRD-Multifunctional (Metallurgy institute El-Tebbin Cairo), using CuK_α beam ($\lambda = 0.1541$ nm) through 2θ (20° - 100°) via Williamson- hall method defined by the following equation [24, 42]:

$$\beta \frac{\cos \theta}{\lambda} = \frac{K}{d_{\text{XRD}}} + 4\varepsilon \frac{\sin \theta}{\lambda} \quad 1$$

Where K is shape factor (~ 0.94), (θ) the Bragg angle, and β is integral breadth. The micro-strain (ε) and the obtained density of dislocation (ρ_D) also studied [21, 31]. The strain distribution over the lattice (η) calculated by considering the Crystallite size and strain persuaded broadening according to Cauchy and Gaussian function [44]. The distribution of antimony and indium into the Al matrix has been investigated by X-ray diffraction and Scanning electron microscope model (JEOL, JSM-5400) (SEM & EDXs laboratory, physics department, faculty of agricultural, Mansoura university). The bulk density of alloys measured by the Archimedes principle. A dynamic resonance method is used to test the young moduli of melt-spun ribbons. The result obtained has been compared with the calculated values using computerized tensile strength (TS) test machine using the static technique[32](Metal physics laboratory, physics department, faculty of science, Mansoura University). Moreover, the comparison shows much coincidence in module calculations. The indentation creep and the Vickers hardness (H_V) has been measured through using the FM-7 micro hardness assessment[26]. Thermal properties for utilizing specimens with a heating rate of 10 K/min has been done using differential scanning calorimetry (DSC)(Metallurgy institute El-Tebbin Cairo). The temperature dependence of resistivity (TDR)(Central laboratory, faculty of science, port-said university) was measured using the TTI BS407 Precision MILLI/ Micro-Ohmmeter 500 microampere that has a high basic

accuracy of 0.1 %, a wide range 1 $\mu\Omega$ to 20 k Ω and a heating cell Max 650°C of temperature controller XMTG-3000.

3. RESULTS AND DISCUSSIONS

3.1 Structural Analysis Phase Identification

The X-ray diffraction (XRD) graphs of the melt-spun samples are presented in Figure 1. The Structural information of the XRD analysis is shown in table 1. The diffraction peaks just displacement their position nevertheless does not increment in the height of peaks, subsequently any modification in cell symmetry. According to the experimentally observed interplanar spacing of the first few strong reflections, which indicate three face-centered cubic (FCC) phases, which are for Al, AlSbIn, InSb, and AlSb IMC (Zincblende_B3 (ZnS)) In (Tetragonal (S.G.: I41/amd)). The IMC AlSb formed due to interacting with Sb and In with the molten Al-matrix. The antimony contribution refines the aluminum crystallite size and cell volume, which is related to strain distribution and lattice strain in the original metal matrix composite. From table 1, the decreasing of Atomic Packing Factor (APF) with 8% tend to build up the balance structure of IMC. Another essential feature is the study of IMC phase stability where falls under the name Hume-Rothery stabilization, which is concerned for the pseudo gap across Brillouin zone - fermi surface interactions. The IMC may occur in amorphous alloys, so the first time proposed a model by Helne et al. [50] upon his studies of the de Haas-van Alphen effect in aluminum. Fermi wave number for the K-space $K_f(\text{\AA}^{-1})$, The volume of fermi sphere $V_f(\text{\AA}^3)$, the volume of Brillouin sphere $V_b(\text{\AA}^3)$ and Brillouin zone diameter $K_{B111}(\text{\AA}^{-1})$ of the maximum relative intensity of Al phase (111) plan. Figure 1 shows that the $\text{Al}_{80}\text{-Sb}_{10}\text{-In}_{10}$ alloy is contained three phases Al, AlSbIn IMC and In which presented in 4, 2, and 3 pecks respectively. There is convergence in crystallite size between the current phases because of the strain disappearance in each formation phase, but the strain distribution and lattice distortion of AlSbIn IMC (the empirical formula is $\text{Al}_{0.5}\text{In}_{0.5}\text{Sb}$) have lager value because of the larger values of crystal system (S.G.: F-43m). The $\text{Al}_{70}\text{-Sb}_{20}\text{-In}_{10}$ alloy is contained four phases Al, AlSb IMC, InSb IMC, and In which presented in 5, 2, 8, and 3 pecks, respectively. The $\text{Al}_{80}\text{-Sb}_{10}\text{-In}_{10}$ alloy has the most significant Brillouin volume and Brillouin zone diameter with the smallest value of Cell Volume, which is in good agreement with the number of atoms per unit cell behavior. So that explains why $\text{Al}_{80}\text{-Sb}_{10}\text{-In}_{10}$ sample is higher in dislocation density with the smallest Crystallite size of In phase. It affects many properties, such as mechanical and electrical properties.

Figure 1: X-Ray Diffraction Patterns of Al-Sb-In Melt-Spun Alloys.

Table 1: The Details of the XRD Analysis of Al-Sb Alloys

Alloy	Phases	The Crystallite Size (nm)	Lattice Strain ($\varepsilon \times 10^{-4}$)	Strain Distribution ($\eta \times 10^{-3}$)	Dislocation Density ($P \times 10^{-4}$) (nm^{-2})	Lattice Parameters		Cell Volume ($\text{\AA}^3$)	Number of Atoms per unit cell of Aluminum phase (N)	Atomic Packing Factor APF
						a ($\text{\AA}$)	c ($\text{\AA}$)			
Al ₈₀ -Sb ₁₀ -In ₁₀	Al	29.54	15.55	11.85	19.99	4.056		66.733	3.859	0.714
	AlSbIn	27.63	28.02	27.64	12.15	6.274		247.03	14.28	-
	In	24.95	19.85	18.46	2.72	3.258	4.98	52.33	3.02	-
Al ₇₀ -Sb ₂₀ -In ₁₀	Al	39.15	11.54	2.16	6.70	4.071		67.459	3.770	0.678
	AlSb	30.80	27.07	7.11	18.45	6.170		234.90	13.13	-
	InSb	30.96	15.13	2.80	6.83	6.491		273.59	15.29	-
	In	28.18	16.88	3.76	10.89	3.253	4.98	52.333	2.92	-

Surface Morphology

Figure 2 shows SEM images of the seven prepared melt-spun alloys. Al phase presented in dendritic arms and the dark areas and the diffused aspect bright regions of the AlSb, InSb addition granules were formed. Table 2 shows SEM correlation parameters of Al particles as a function of Sb content were analyzed using a program by NIH ImageJ as an open source based on Fiji "Is Just ImageJ—Batteries included"[28, 43] according to the particle analysis protocol. By additive indium element to Al₉₀-Sb₁₀ and Al₈₀-Sb₂₀ alloys formation nonhemogenic phase present in indium in Figure 2.i contract with Al₇₀-Sb₂₀-In₁₀ alloy the indium element united with antimony to formation InSb IMC phase and presented in high bright regions Figure 2.j. It is as follows calibration of scale bar for all images with the same magnification and chooses an appropriate threshold to differentiate the phases and separate each one to analysis then indexed in Table 2. The delaminating mechanism of bright (AlSb, InSb Phases) and dark (Al-rich areas) becomes equiaxed dendritic due to correlating the parameters like grain-sized, perimeter, and circumference (Circularity) with the formatting of IMC. The slighter perimeter and grain-sized are spreading entirely with the matrix of (10 wt% Sb, In), which can reduce the size of the dark grains, which is powerfully linked to the mechanical properties. These comments are in decent pact by crystallite size behavior. As seen in Figure 2.i, the dendrite AlSbIn phase diminishes, the atomic number contrast revealed the trapping of Sb and In particles within Al layers and existed the porosity. Consequently, obstacles s number compared to the grain boundary movement rise with the particle size reduction, leading to a small movement of the grain boundary. The proportion of the InSb IMC phase in the crystal volume is relative to the crystal boundary. The deformation intensifies inter-diffusion, and the primary dislocation density increases the free energy of both pure components and intermetallic compounds, but therefore a melt-spun technique improves it.

Figure 2: SEM Images (i) Al₈₀-Sb₁₀-In₁₀ and (j) Al₇₀-Sb₂₀-In₁₀ Alloys.

Table 2: The Microstructural Parameters Analysis for Al-Sb-In Alloys Calculated using an NIH ImageJ for Data Visualization and Analysis tool (Fiji Is Just ImageJ—Batteries Included)

Alloy	Phases	Average Grain size (μm)	Percentage Area %	Average Perimeter (μm)	Average Circularity	Average Solidity
Al ₈₀ -Sb ₁₀ -In ₁₀	Al	4.651 $\pm$ 0.03	59.93	8.351 $\pm$ 0.06	0.70	0.85
	AlSbIn	0.335 $\pm$ 0.04	11.98	3.186 $\pm$ 0.04	0.82	0.85
	In	1.816 $\pm$ 0.02	24.17	3.163 $\pm$ 0.02	0.85	0.86
Al ₇₀ -Sb ₂₀ -In ₁₀	Al	2.377 $\pm$ 0.05	26.08	5.851 $\pm$ 0.53	0.72	0.83
	AlSb	1.079 $\pm$ 0.02	14.615	3.707 $\pm$ 0.02	0.78	0.84
	InSb	1.171 $\pm$ 0.04	54.34	4.19 $\pm$ 0.05	0.75	0.85

Electrical Properties

The electrical resistivity is one of the transport phenomena. The temperature dependence of the electrical resistivity (ρ) of prepared alloys (Figure 3). The samples studied at temperatures ranging from 350 to 533 K with a detailed analysis of electrical resistivity ρ ($\Omega \cdot \text{m}$) The temperature coefficient of resistivity T.C.R (K^{-1}), Thermal conductivity (K) and Thermal effusivity ($\text{W}/\text{S}^{\frac{1}{2}}\text{m}^2\text{K}$) Also, tabulated in Table 3. According to XRD data, there are AlSb IMC particles finely dispersed in Al-matrix.

Table 3. Electrical properties: Electrical Resistivity (ρ) at Room Temperature and Temperature Coefficient (α) per k of Al-Sb-In Alloys

Alloy	ρ ($\Omega \cdot \text{m}$) $\times 10^{-8}$	TCR (K^{-1}) $\times 10^{-3}$	Thermal Conductivity (K) (W/m K)	Thermal Effusivity ($\text{W}/\text{S}^{\frac{1}{2}}\text{m}^2\text{K}$) $\times 10^{-3}$
Al ₈₀ -Sb ₁₀ -In ₁₀	8.80 $\pm$ 0.25	2.04	17.12	4.78 $\pm$ 0.42
Al ₇₀ -Sb ₂₀ -In ₁₀	10.30 $\pm$ 0.9	1.80	14.65	4.65 $\pm$ 0.45

The IMC and lattice distortions defects in solid solution due to thermal vibrations and impurities effect on electrical resistivity according to Matthiessen's rule. The precipitates, dislocations, and grain boundaries deliver an essential contribution to the total resistivity[18, 23, 38]. It is found electrical resistivity varied from 8.80 to 10.30 $\times 10^{-8}(\Omega \cdot \text{m})$. on the other hand, the majority of fermi parameters depend on Valance Electron Concentration VEC while a few parameters like Relaxation time (τ) moreover, Mobility (μ) depend on electrical conductivity. The role of IMC AlSb clear appears an effect on decreasing the mobility which in turn effect on relaxation time and Electron specific heat (C_e)It has a good congregate with the formation of IMC, which is found on the surfaces of these ribbons, as shown in SEM figures in the delaminating mechanism. However, with the formation of AlSbIn IMC, the ρ values have been decreased, which is presented. The highest ρ value was for Al₈₀-Sb₂₀-In₁₀ alloy, which is due to the formation of two IMC phases, which are AlSb and InSb, presented in concentration (10 peaks). The role of AlSb IMC clear appear and effect on decreasing the mobility which in turn effect on relaxation time and Electron specific heat (C_e), so its values converge with the formation of IMC after rapid decline compared to the pure Al matrix sample value. The stability for the specific heat of electrons and Temperature Coefficient Resistance over all samples, but it is increasing in Al₈₀-Sb₁₀-In₁₀ alloy, which is due to formation AlSbIn IMC and due to its lattice distortion.

Table 4. Fermi Parameters: Valance Electron Concentration (VEC), Electron Density (n), Fermi Wave Vector (Kf), Fermi Energy (Ef), Fermi Velocity (Vf), Relaxation time (τ), and Fermi Temperature (Tf), Electron Specific Heat (C_e) of Al-Sb-In Alloys

Alloy	Valance Electron Concentration	(n) $\times 10^{28}$ (m^{-3})	Mobility (μ) ($m^2/V.S$) 10^{-4}	Relaxation time (τ) $\times (10^{-15})$ s	Fermi energy E_F (eV)	Fermi wave Vector (K_f) $\times 10^{10}$ (m^{-1})	Fermi Velocity (V_f) (m/s) $\times 10^6$	Fermi Temperature ($T_f(K)$) $\times 10^4$	Electron Specific Heat (C_e) ($J/mol.K$) $\times 10^{-2}$
Al ₈₀ -Sb ₁₀ -In ₁₀	3.056	18.86	3.95	2.25	11.62	1.746	2.052	13.44	2.91
Al ₇₀ -Sb ₂₀ -In ₁₀	3.115	18.89	3.37	0.103	11.64	0.994	2.053	4.372	2.90

Figure 3: The Temperature Dependence of Resistivity of Al-Sb-In Alloys.

Mechanical Behavior

The mechanical study is divided into two essential parts:

Elastic Moduli and Internal Friction by Dynamic and Static Techniques

A dynamic method by DRT be contingent on the particles and does not need the strength of the important influence because it depends on the vibration of atoms and molecules, So it is an effective way to assign the young moduli and the internal friction Q^{-1} [8, 25, 27, 48]. A static technique is called tensile strength (TS) always have a more significant effect than the first method on samples. The density of alloys calculated accordance with the ASTM E373 and ASTM B527-15 [2, 13, 41], standard with the help of the Archimedes method using distilled water which listed in table 5. From XRD data and SEM images, there is IMC AlSb crystallite dispersed in Al-matrix and refine the grain size of AlSb, which improves the mechanical properties. So the result has been confirmed by two measuring systems (DRT) and Tensile Strength (ST), which is known with stress-strain analysis shown in Figure 4 and Figure 5, respectively. All mechanical parameters and their calculation are summarized in table 5 and table 6 for all of the prepared alloys.

The formation of the IMC gradually reduced the young modulus, so the Debye Temp (Θ_D) and Lamé's constant (λ) are correlated to the young modulus. There is a close match between the values of young modulus in two methods. The large size of grains of the AlSb phase has a particular impact on internal fraction and thermal diffusivity, which had the best agreement with strain distributions and density dislocation at $Al_{80} - Sb_{10} - In_{10}$ and $Al_{80} - Sb_{20} - In_{10}$. On the other hand, from Figure 5, there is fluctuation in toughness which the refinement of AlSbIn grain size, so its effects on absorbed energy before rupturing point through the plastic region to record the lowest value at $Al_{80} - Sb_{10} - In_{10}$ sample with (4.57 J/m^3) which also correlates with hardening ratio. The addition of Sb on the Aluminum alloy shows stability in the internal friction until additive of 20% Sb and decrease in the number of AlSb IMC phase and return slight increase in the internal friction until formation AlSbIn IMC in $Al_{80} - Sb_{10} - In_{10}$ returns to decrease. Because of IMCs' shrinking cavities and decreasing of IMCs' grain size while in $Al_{70} - Sb_{20} - In_{10}$ alloy system, a result of the existing two IMC the internal friction increasing again. The considerable fluctuation in the thermal diffusivity has been measured as shown in table 5 and The $Al_{70} - Sb_{20} - In_{10}$ alloy system has Young's modulus value lowest than other alloys, which is related to cell volume contraction and the number of atoms per unit cell decreasing. The magnitude of elastic constants defect-free metal alloys is only a function of the magnitude of the toughness of the atomic bonds. In real polycrystalline melt-spun alloys, other factors such as porosity, the concentration of impurities, intermetallic phases, and alloying elements may influence the magnitude of the elastic constants. The nominal elastic modulus value for Al and its alloys commonly is taken as 69 GPa, but experimental values collected from literature for pure aluminum and its alloys can vary between 40-72 GPa [16, 22]. It is noted in this study that, by the addition of Sb, the elastic modulus slightly decreases, while the addition of 10 wt% In produces a significant decrease by about 25% from the value of the binary alloy. It is well known that Young's modulus is determined by the bonding force among atoms, so this bonding force is not only related to the crystal structure but also the distance among atoms, it can be affected by alloying additions and formation IMC phases [47]. The unit-cell volume of Al-phase is expanded with the addition of Sb content that means that the increased unit-cell volume with Sb content typically leads to decrease elastic modulus of the studied alloy in this study. It is found that Sb atoms tend to interact much actively with In to form a low melting point intermetallic compound [1]. Therefore, a small amount of In is added to melt in this study to facilitate the formation of metallic compound InSb. Hence, it is reported to decrease the elastic modulus of the $Al_{70} - Sb_{20} - In_{10}$ melt-spun.

Micro Creep and Microhardness

Table 5 illustrates approximately parameters were direct to indentation creep behavior of the melt-spun alloys exponents can be derivative from Sargent and Ashby [33] diagram for the melt-spun alloys. The ability to resist plastic deformation increased with the formation of IMC; the stress exponent (n) reduction has indicate for the deformation of creep behavior from dislocation climb grains to diffusional or grain boundary sliding which has an increasing impact on creep resistance. The creep rate has been decreased with In additions, as shown in table 5. The $Al_{70} - Sb_{20} - In_{10}$ alloy has the higher creep rate which is equal to 11.50×10^{-4} .

This is confirming those results at the stress-strain curves, and the above interpretation of any alloy imply the capability to balance between external and internal metamorphosis based on the temperature [46]. Figure 7 demonstrations time up against the strain around to 80 s at fixed load (25 gf), it detected only two regions. The first stage (elastic and plastic strains) and steady-state creep (second stage) tend to become more nearly to constant creep rate where is equivalent to steady-state stage s' slop. The third stage does not occur because of the small applying loading value and time figured in Figure 7 are similar to the typical creep curve for strain. The hardness assessment is a compression technique, so the rupture of samples

does not happen. According to the power-law creeps, an increase in creep rate, and strain rate sensitivity is owing to a decrease in yield strength [6, 40]. Confirmation to that it is noticed from the structure of $\text{Al}_{80}\text{-Sb}_{10}\text{-In}_{10}$ alloy in table 6 to their structure by X-ray diffraction that this alloy has a much lower average crystallite size comparing with $\text{Al}_{70}\text{-Sb}_{20}\text{-In}_{10}$. Not only crystallite size but also compare in grain size recorded in Table 1 had the same behavior, so there is a relationship between the grain size and creep resistance of the base metal [35]. The hardness tests result for Al-Sb based alloys, as seen in table 5, which consisted of creep resistance behavior. As we mentioned before, Juhasz et al. carried-out testes on alloys using Vickers testes to investigate the power-law indentation creep behavior by measuring the stress exponent (n) in steady-state creep using. The rate of diagonal variation is plotted against the Vickers hardness number on a double logarithmic scale, as shown in Figure 6, Al-based alloys. A straight line of slope equal (n) is obtained for each melt-spun alloy.

Table 5: Mechanical Parameters by Dynamic Resonance Technique and Creep Parameters of Al-Sb-In Alloys.

Alloy	Density (g/cm ³)	E (GPa) by DRT	$Q^{-1} \times 10^{-2}$	Thermal Diffusivity (m ² /s) $\times 10^{-7}$	Debye Temp (°D)	Lame's Constant (λ) (GPa)	H _v (MPa)	Maximum Shear Stress (Pa)	Compressive yield Strain $\epsilon_{c,y} \times 10^{-3}$	Creep Stress Exponent (n)	$\epsilon \times 10^{-4}$ at 25 gf
$\text{Al}_{80}\text{-Sb}_{10}\text{-In}_{10}$	3.06	59.27	1.20	3.69	345	59.04	493	159.05	2.59	4.46	11.50
$\text{Al}_{70}\text{-Sb}_{20}\text{-In}_{10}$	3.27	56.12	2.40	4.62	322	59.62	416	135.04	2.12	8.92	5.97

Table 6: Mechanical Parameters by Static Technique.

Alloy	E (GPa) by TS	Yield Strength (MPa)	UTS (MPa)	Resilience U _r (Pa)	Toughness (J/m ³)	Ductility (%EL)	CSFS* von Mises Criterion (τ°) (Mpa)	Strength Coefficient (Mpa)	Strain Hardening
$\text{Al}_{80}\text{-Sb}_{10}\text{-In}_{10}$	63.60	201.54	288.63	3.20	4.57	3.99	116.36	114.33	0.37
$\text{Al}_{70}\text{-Sb}_{20}\text{-In}_{10}$	65.40	209.05	218.19	11.72	25.00	4.58	120.70	82.94	0.69

Figure 4: Typical Resonance Curves based Hyper-Eutectic Al-Sb-In Melt-Spun Alloys.

Figure 5: Stress-Strain Curves of Al-Sb-In Alloys.

Figure 6: Ln–Ln Plot of the Rate of Diagonal Variation Against the Vickers Hardness Numbers for Melt-Spun Al-Sb-In Alloys.

Figure 7: Strain Variation vs. Loading Time of Al-Sb-In Alloys.

Thermal Properties

Figure 8 and Figure 9 show the thermal flux flow of alloys gained in temperature up to 700 °C with a heating system rate of 10 °C/min. The melting temperature (T_m) of $\text{Al}_{90-x}\text{-Sb}_x\text{-In}_{10}$ (where $x = 10$ and 20) has declined from 8 to 23 °C compared with the value of pure aluminum alloy caused for IMCs phase formation. If the pasty temperature zone is wide-ranging, then it designates for a long time during a change in solidification, and it is a distinctive characteristic of aluminum alloys. The onset point in the DSC heat flux flow graph denotes the solidus temperature, and the peak point displays the liquidus temperature [12]. The addition of In has a real effect on the melting temperature, and the effect on the mushy range becomes broader due to Sb and In form intermetallic compounds. The value of the internal energy of fusion (ΔH) was a valuable parameter of industrial applications. The specific heat (C_p) at constant pressure considered for melt-spun alloys from the curve of temperature against heat flux listed in the Table 7. Since non-equilibrium state and intermetallic stage creation where occasioned an alloy mass is m , transferring energy to the alloy is Q , and temperature change through the process is ΔT , then the specific heat (C_p) can attain using these equations 2 [34]. The lowest C_p value was for $\text{Al}_{80}\text{-Sb}_{10}\text{-In}_{10}$ is owing to a small grain size. The excess ΔC_p conforms the experimental law.

$$\Delta C_p = Z[NQ^2/RT^2]e^{-Q/RT} \text{ Eqn.}$$

2

Where R is the universal gas constant, N is the number of atoms displaced from the equilibrium position, Q is the ordering activation energy, and Z is the coordination number, The straight lines resulting from the $\ln(\Delta C_p T^2)$ vs $1000/T$ for all alloys shown in Figure 10 The additional materials change the thermal activation energy Q (Table 7). Another simple method to estimate the activation energy which was designated by Borchardt et al. [3] for solutions and by Perkin-Elmer instrument [49] for solids by differential scanning calorimetry (DSC). It was derived by Kissinger et al. and Rogers et al. [19, 29] and was called by DSWALT method, it was concerned about first-order reactions of non-volatile materials. The first-order form used by Coats et al. and DSWALT et al. [5, 7, 30] for obtaining E_A . There are effects of In addition to this; alloys produced two IMC phase AlSbIn and InSb addition to AlSb. The aluminum-antimonide phase did not appear in binary Al-Sb alloys may due to the complete solubility in the aluminum phase. If the pasty temperature zone is wide-ranging, then it designates for a long time during a change in solidification, and it is a distinctive characteristic of aluminum alloys. The onset point in the DSC heat flux flow graph denotes the solidus temperature, and the peak point displays the liquidus temperature [12]. The addition of Sb has a real effect on the melting temperature, and the effect on the mushy range becomes broader due to Sb form intermetallic compounds with Al. The value of the internal energy of fusion (ΔH) was a valuable parameter of industrial applications.

Table 7: Thermal Parameters of Al-Sb-In Alloys

Alloy	Phases	T_m (°C)	ΔH (J/g)	C_p (J/g.k)	ΔT (°C)	E_A (KJ/mol)	ΔS (J/g.k)	Q (KJ/mol)
Al ₈₀ -Sb ₁₀ -In ₁₀	Al	639.46	255.4	0.435	11.75	105.05	8.91	288.34
	AlSbIn	702.51	36.91	0.023	28.48	101.06	1.21	167.37
Al ₇₀ -Sb ₂₀ -In ₁₀	Al	653.12	260.3	0.450	26.31	105.20	9.90	338.84
	AlSb	526.16	2.996	0.006	10.04	101.08	0.13	300.23
	InSb	491.88	1.765	0.005	3.48	102.54	0.08	499.70

Figure 8: DSC Curve for Al₈₀-Sb₁₀-In₁₀ Alloy. Figure 9: DSC Curve for Al₇₀-Sb₂₀-In₁₀ Alloy.

Figure 10: $\ln(\Delta C_p T^2)$ vs. $1000/T$ for all the Al-Sb-In Alloys.

CONCLUSIONS

The present work demonstrated that the Sb and In embedded into the Al matrix with the formation of a unique stoichiometric AlSb, AlSbIn, and InSb IMC composition influenced the mechanical of samples prepared by chill block melt-spun technique at 850 °C. It proved with X-ray analysis, which is generally obtained under equilibrium conditions. The AlSb formation through increasing microstrain, dislocation density refines the structure of the alloys. It is predicted a change in mechanical property due to the difference in structure and due to the higher fusion alloys entropy. Also, according to the phase diagram for all ratios used in the present work with Al/AlSb eutectic matrix (Figure 1) because of non-equilibrium solidification effects. After Indium additive to $\text{Al}_{90}\text{-Sb}_{10}$ and $\text{Al}_{80}\text{-Sb}_{20}$ and rapidly solidified, it noticed that the improvement, and further

uniform spreading for AlSb and InSb. Hardness and Elastic moduli of semiconductor alloys depend on the size, distribution, and the concentration of the AlSbIn, AlSb, and InSb. Elastic moduli of Al₈₀-Sb₁₀-In₁₀ alloy have been decreased due to AlSbIn IMCs formed, also their absorption ability of energy before deformation decreased. The AlSb shape by raising the microstrain and the alloy microstructure. It is foreseen a change in electrical property due to the difference in structure and Entropy because of higher fusion alloys. Adding ten wt% of Sb is demonstrated on transform dendrites to fine particles, an average grain size refined almost. According to the Hume-Rothery role of stability, which is connected to valence electron concentration, slightly increasing behavior, so it affects all Fermi parameters. The relatively stable action, however, is slightly reduced in all samples above 20 wt% of Sb in electrical conductivity. The Al₈₀-Sb₁₀-In₁₀ and Al₇₀-Sb₂₀-In₁₀ quenched ribbons showed high potential as electro-optical devices only with a further modification of compositions for improvement of electrical and thermal behavior to enhance the safety measures. However, the best one is Al₇₀-Sb₂₀-In₁₀ and suggesting the practicability of using Al₇₀-Sb₂₀-In₁₀ in designing a junction useable in the multijunction solar cell.

REFERENCES

1. Alper Billur C, Gerçekcioglu E, Bozoklu M, Saatçi B, Ari M, Nair F (2015) The electrical, thermal conductivity, microstructure and mechanical properties of Al-Sn-Pb ternary alloys. *Solid State Sciences* 46:107–115. doi: 10.1016/j.solidstatesciences.2015.06.005
2. Archimedes Archimedes. *The Works of Archimedes* xv–xxii
3. Borchardt HJ, Daniels F (1957) The Application of Differential Thermal Analysis to the Study of Reaction Kinetics. *Journal of the American Chemical Society* 79:41–46. doi: 10.1021/ja01558a009
4. Chen J, Du Z, Tey ZHJ, Lin F, Hoex B, Aberle AG (2012) Impact of aluminium thickness on the Al-Si alloy formation of aluminium local back surface field silicon wafer solar cells. 27th European Photovoltaic Solar Energy Conference and Exhibition, Frankfurt, Germany 1217–1220. doi: 10.4229/27thEUPVSEC2012-2AV.6.10
5. Coats AW, Redfern JP (1964) Friction and transfer of polytetrafluoroethylene. *Nature* 201:1172. doi: 10.1038/201464a0
6. Cseh G, Bär J, Gudladt HJ, Lendvai J, Juhász A (1999) Indentation creep in a short fibre-reinforced metal matrix composite. *Materials Science and Engineering A* 272:145–151. doi: 10.1016/S0921-5093(99)00466-9
7. Duswalt AA (1974) The practice of obtaining kinetic data by differential scanning calorimetry. *Thermochimica Acta* 8:57–68. doi: 10.1016/0040-6031(74)85072-0
8. E1875-08 (2013) Standard Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio by Sonic Resonance. *ASTM International* 1–9. doi: 10.1520/E1875-08.2
9. Ferhat M (2004) Computational optical band gap bowing of III–V semiconductors alloys. *physica status solidi (b)* 241:R38–R41. doi: 10.1002/pssb.200409048
10. Glisson TH, Hauser JR, Littlejohn MA, Williams CK (1978) Energy bandgap and lattice constant contours of iii–v quaternary alloys. *Journal of Electronic Materials* 7:1–16. doi: 10.1007/bf02656016
11. Green MA, Emery K, Hishikawa Y, Warta W, Dunlop ED, Levi DH, Ho-Baillie AWY (2017) Solar cell efficiency tables (version 49). *Progress in Photovoltaics: Research and Applications* 25:3–13. doi: 10.1002/pip.2855
12. Huang K, Zhou H (1999) The Variability of Optically Selected QSO Sample. *Symposium - International Astronomical Union* 194:172–174. doi: 10.1017/S0074180900161947
13. International ASTM Standard (2015) ASTM B527 - 15. Standard Test Method for Tap Density of Metal Powders and

Compounds. ASTM International

14. Jia R (2017) *Properties of thin film III-V / IV semiconductor alloys and nanostructures* By
15. Jones H (1984) *The status of rapid solidification of alloys in research and application. Journal of Materials Science* 19:1043–1076. doi: 10.1007/BF01120015
16. Kamal M, Fouda SE (2013) *Structural and Mechanical Characteristics of Al -Pb Alloys produced by chill-Block melt spinning. International Journal of Engineering & Technology* 13
17. Kamal M, S. Mohammad U (2012) *Chill-Block Melt Spin Technique. Bentham Science Publishers*
18. Kamal, Mustafa, and RIZK MOSTAFA Shalaby. "Effect of reactive metal on creep resistance of Sn-50Bi lead free solder alloys." *Int. J. Phys. Res* 4 (2014): 19-28.
19. Kamal, Mustafa, and Rizk Mostafa Shalaby. "Effect of Indium Addition on the Physical Properties of Al-Pb Bearing Alloys Rapidly Quenched from Melt." *International Journal of Physics and Research (IJPR)* 4.6, Dec 2014, 37-46
20. Karabay S, Önder FK (2004) *An approach for analysis in refurbishment of existing conventional HV-ACSR transmission lines with AAAC. Electric Power Systems Research* 72:179–185. doi: 10.1016/j.epsr.2004.03.014
21. Kissinger HE (1956) *Variation of peak temperature with heating rate in differential thermal analysis. Journal of Research of the National Bureau of Standards* 57:217. doi: 10.6028/jres.057.026
22. Kuech TF (2016) *III-V compound semiconductors: Growth and structures. Progress in Crystal Growth and Characterization of Materials* 62:352–370. doi: 10.1016/j.pcrysgrow.2016.04.019
23. Kumar NK, Roy B, Das J (2015) *Effect of twin spacing, dislocation density and crystallite size on the strength of nanostructured α -brass. Journal of Alloys and Compounds* 618:139–145. doi: 10.1016/j.jallcom.2014.08.131
24. Lasagni F, Degischer HP (2010) *Enhanced Young's modulus of Al-Si alloys and reinforced matrices by co-continuous structures. Journal of Composite Materials* 44:739–755. doi: 10.1177/0021998309347649
25. Lu L, Shen Y, Chen X, Qian L, Lu K (2004) *Ultrahigh Strength and High Electrical Conductivity in Copper. Science* 304:422–426. doi: 10.1126/science.1092905
26. Mahmoud EK, Ebeid MR, Kaid MA, Ali MGS (2015) *Broadening Microstructure Analysis Program (BMAP): An isotropic and anisotropic crystallite size and strain calculator. Journal of Applied Crystallography* 48:1729–1733. doi: 10.1107/S1600576715016696
27. Nuttall K (1971) *The damping characteristics of a superplastic Zn-Al eutectoid alloy. Journal of the Institute of Metals* 99:266–270
28. Per SC (1998) *The Marketplace for Surface Technology . New and Used Process Equipment & Machinery . Future Tech Group FM7 Micro Hardness Tester Future Tech Group FM7 Micro Hardness Tester. 1–2*
29. Riley WF (1975) *Book Reviews : ELASTIC CONSTANTS AND THEIR MEASUREMENT* E. Schreiber, O. L. Anderson, and N. Soga McGraw-Hill Book Co., New York, N. Y. (1973). *The Shock and Vibration Digest* 7:120–120. doi: 10.1177/058310247500700113
30. Rishi Kumari, Narinder Rana (2015) *Particle Size and Shape Analysis using Imagej with Customized Tools for Segmentation of Particles. International Journal of Engineering Research and V4:247–251. doi: 10.17577/IJERTV4IS110211*
31. Rogers RN, Morris ED (1966) *On Estimating Activation Energies with a Differential Scanning Calorimeter. Analytical Chemistry* 38:412–414. doi: 10.1021/ac60235a009

32. Rogers RN, Smith LC (1967) Correction. Estimation of Preexponential Factor from Thermal Decomposition Curve of an Unweighed Sample. *Analytical Chemistry* 39:1405. doi: 10.1021/ac60256a050
33. Roh A, Um HY, Kim D, Nam S, Kim HS, Choi H (2017) Influence of high-pressure torsion and hot rolling on the microstructure and mechanical properties of aluminum–fullerene composites. *Journal of Materials Science* 52:11988–12000. doi: 10.1007/s10853-017-1230-3
34. Saad G, Fayek SA, Fawzy A, Soliman HN, Mohammed G (2010) Deformation characteristics of Al-4043 alloy. *Materials Science and Engineering A* 527:904–910. doi: 10.1016/j.msea.2009.09.018
35. Saha, Nandini, et al. "Comparative Study of IV-Characteristics of PIN Diode at Different Doping Concentrations for Different Semiconductor Materials Using TCAD." *International Journal of Electronics and Communication Engineering (IJECE)* 4.6 (2015): 1-8.
36. Shakeera Banu M, Sujatha K, Sridharan G, Manikandan R (2013) Antihyperglycemic and antihyperlipidemic potentials of *Psidium guajava* in alloxan-induced diabetic rats. *Asian Journal of Pharmaceutical and Clinical Research* 6:88–89. doi: 10.1179/026708392790171107
37. Shalaby RM (2005) Correlation between thermal diffusivity and activation energy of ordering of lead free solder alloys Sn65-xAg25 Sb10Cu rapidly solidified from molten state. *Journal of Materials Science: Materials in Electronics* 16:187–191. doi: 10.1007/s10854-005-0763-4
38. Shalaby RM (2015) Indium, chromium and nickel-modified eutectic Sn–0.7 wt% Cu lead-free solder rapidly solidified from molten state. *Journal of Materials Science: Materials in Electronics* 26:6625–6632. doi: 10.1007/s10854-015-3261-3
39. Sundaresan R, Froes FH (1987) *Mechanical Alloying*
40. Tanabe K (2009) A review of ultrahigh efficiency III-V semiconductor compound solar cells: Multijunction tandem, lower dimensional, photonic up/down conversion and plasmonic nanometallic structures. *Energies* 2:504–530. doi: 10.3390/en20300504
41. Valiev RZ, Murashkin M, Sabirov I (2014) A nanostructural design to produce high-strength Al alloys with enhanced electrical conductivity. *Scripta Materialia* 76:13–16. doi: 10.1016/j.scriptamat.2013.12.002
42. Vurgafman I, Meyer JR, Ram-Mohan LR (2001) Band parameters for III-V compound semiconductors and their alloys. *Journal of Applied Physics* 89:5815–5875. doi: 10.1063/1.1368156
43. Walser B, Sherby OD (1982) The Structure dependence of power law creep. *Scripta Metallurgica* 16:213–219. doi: 10.1016/0036-9748(82)90389-1
44. Wenzel TJ (2013) Douglas A. Skoog, Donald M. West, F. James Holler, and Stanley R. Crouch: *Fundamentals of analytical chemistry*, 9th ed., international ed. *Analytical and Bioanalytical Chemistry* 405:7903–7904. doi: 10.1007/s00216-013-7242-1
45. Williamson GK, Hall WH (1953) X-ray line broadening from filed aluminium and wolfram. *Acta Metallurgica* 1:22–31. doi: 10.1016/0001-6160(53)90006-6
46. Xu L, Feng Y, Fan Z, Yun D (2014) Research into the grading method of kiwi fruit based on volume estimation and surface defect. *INMATEH - Agricultural Engineering* 44:93–102. doi: 10.1038/nmeth.2089
47. Youssef KM, Scattergood RO, Murty KL, Koch CC (2006) Nanocrystalline Al-Mg alloy with ultrahigh strength and good ductility. *Scripta Materialia* 54:251–256. doi: 10.1016/j.scriptamat.2005.09.028
48. Zhang J, Li Y, Zhang Q (2018) Properties and microstructure changes in Au-Cu-based alloy with indium addition. *Journal of Alloys and Compounds* 734:81–88. doi: 10.1016/j.jallcom.2017.11.018

49. Zhang P, Li SX, Zhang ZF (2011) General relationship between strength and hardness. *Materials Science and Engineering A* 529:62–73. doi: 10.1016/j.msea.2011.08.061
50. Zhou YL, Niinomi M, Akahori T (2004) Effects of Ta content on Young's modulus and tensile properties of binary Ti-Ta alloys for biomedical applications. *Materials Science and Engineering A* 371:283–290. doi: 10.1016/j.msea.2003.12.011
51. (1952) *Theory of Elasticity*. Timoshenko and Goodier. McGraw-Hill. New York 1951. 493 pp. 270 diagrams. 81s. net. (New Edition.). *Journal of the Royal Aeronautical Society* 56:308. doi: 10.1017/S036839310012471X
52. (1955) *The perkin-elmer instrument digest*. *Analytical Chemistry* 27:20. doi: 10.1021/ac60101a721
53. (2000) *The science of alloys for the 21st century: a Hume-Rothery symposium celebration: proceedings of a symposium sponsored jointly by the Electronic, Magnetic, and Photonic Division (EMPMD) ... [et al.]*. TMS, Warrendale, Pa