Journal of Inventive and Scientific Research Studies (JISRS)
www.jisrs.com Vol: IV, Issue: 3 September 2026 ISSN: 2584-0630 (Online)

$AL_{1-X}IN_XSB$ SEMICONDUCTOR ALLOY FOR EMERGING QUANTUM COMPUTING

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Received: June 16, 2026, **Accepted**: September 11, 2026, **Online Published**: September 30, 2026

ABSTRACT

In the $Al_{1-x}Sb$ alloy, the melting point drops linearly as the Al concentration rises. Designing quantum materials with specialized thermal conductivity requires this thermal tunability. This regulates qubit behaviour in different temperature environments. Epitaxial growth of hetero structure and quantum dot layers with regulated temperature and lattice expansion. As the Al concentration (X) rises in the ternary alloy $Al_{1-x}In_xSb$, the data show a nearly linear drop in melting point. Because of its tunable electrical and thermal properties, the ternary III–V semiconductor alloy $Al_{1-x}In_xSb$ (where $0 \leq x < 1$) is receiving a lot of attention in the design of hardware for quantum computing. Indium doping (increasing x) improves qubit stability and scalability. InSb has a low bandgap (~0.17 eV), whereas AlSb has a broad bandgap (~1.6 eV). The bandgap narrows as the indium concentration (x) rises, enabling low-energy spin qubits and heterostructures that can be adjusted for topological quantum computing. Application: Tunneling barriers in quantum dots and Josephson junctions can be precisely controlled thanks to band gap narrowing.

Keywords: Indium Doping, AlInSb, Quantum Computing Alloy, and Hetero Structures

PACS Codes: 03.67.Lx, 73.20.Dx, 76.60.-k

Introduction

Compositions that are rich in $Al_{1-x}In_xSb$ come close to InSb's remarkable electron mobility ~77,000 cm²/V·s at 300K. High mobility is essential for reducing decoherence in solid-state qubits, enabling quantum processors to perform gate operations more quickly. Enhances fidelity and lowers noise in qubit manipulation and readout—Lattice Matching with Buffer Layers. Indium doping enables lattice tailoring to fit substrates such as GaSb, InAs, or AlInSb. This reduces interface flaws during epitaxial growth, which is crucial for Arrays of quantum dots. Quantum well heterostructures reduce lattice-mismatch strain and improve coherence time. The thermoelectric melting point can be adjusted. As your previous results showed, increasing In (and lowering Al) lowers the melting point, enabling integration with cryogenic quantum systems and low-temperature growth. For Instance, $Al_{1-x}In_xSb$ with x = 0.5 has a melting point close to 1064°C.

Methodology

For instance, when constructing stable quantum devices—such as spin qubits, quantum dots, and hybrid superconducting systems—where cryogenic operation and low thermal noise are crucial, the thermal behavior of $Al_{1-x}In_xSb$ alloys is crucial. Thermal properties that are frequently determined include melting point (Tm), specific heat capacity (Cp), thermal conductivity (κ), thermal expansion coefficient (α), and thermal diffusivity (D). The Bridgman-Stockbarger approach, Molecular Beam Epitaxy (MBE), or Metal Organic Vapor Phase Epitaxy (MOVPE) are used to create alloys with different x ($0.0 \leq x \leq 0.5$). GaSb, AlSb, or lattice-matched buffer layers are examples of substrates. Differential Thermal Analysis (DTA)/DSC: The onset melting point (Tm) is indicated by an endothermic peak. Heat capacity (Cp) was measured as a function of temperature (often 300–800 K) using differential scanning calorimetry (DSC). Laser Flash Analysis (LFA) was used to assess the thermal conductivity (κ).

A quantum computing dilution refrigerator is an essential instrument for quantum computing and low-temperature condensed matter physics because it provides continuous cooling down to the millikelvin range (~5–20 mK). Semiconductor alloys play important roles in such refrigerators, both as structural/electronic materials and as integration components for quantum devices, Including Quantum Device Integration, Thermal Anchoring, Wiring Materials, Superconducting Proximity, Hybrid Devices, Noise Reduction, Decoherence Control, and Practical Applications.

In this Research work, we host semiconductor-based qubits in dilution

refrigerators for quantum computing. Materials research: studying semiconductor alloy properties at ultra-low temperatures. Detector technology: semiconductor alloys in low-temperature bolometers and photon detectors for astronomy & medical imaging.

Results and Discussion:

As the concentration of Indium (In) increases, κ falls, which leads to increased phonon scattering because of alloy instability. Cp somewhat rises with x, improving the device layers' ability to absorb heat. In order to match thermal expansion with substrates in quantum hetero structures, α must grow with x. Low thermal conductivity and thermal stability suppress decoherence. Accurate Cp and κ data are essential for thermal simulation of cryogenic quantum processors. At low temperatures, proper α adjustment avoids mechanical strain in hetero structures.

Quantum Circuit: $Al_xIn_{1-x}Sb$ Semiconductor Alloy Quantum Circuit components

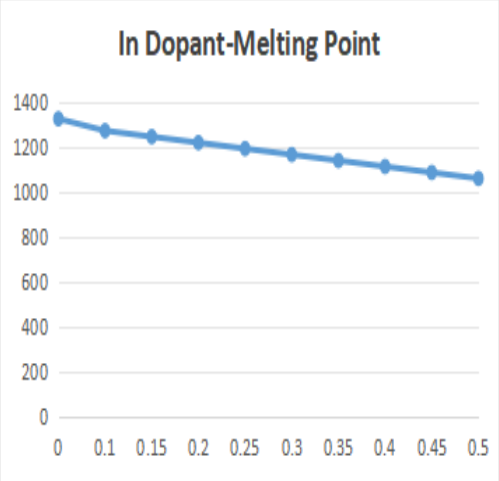
Layer Stack: Al, In & Sb, Top Gate Layer: Ti/Au or Al, Dielectric, $Al_xIn_{1-x}Sb$ Quantum Well with Dimension 15 nm, AlSb Barrier Layer, Substrate of GaSb or InSb Substrate, Qubit Type of Spin qubit in quantum dot array, Operation Temperature from 10 mK to 1 K. The present investigation relates Band Energy Gap and Electro Negativity with variation of Dopant composition for III-V and II-VI Ternary Semiconductor Alloys.Base Alloy: $Al_xIn_{1-x}Sb$ III – V semiconductor alloy with an adjustable bandgap. Tuned via Al concentration (x) for optimal qubit operation. High Electron Mobility is Beneficial for spintronic and topological qubits.

Sl.No	In Dopant Concentration (X)	Melting Point $Al_{1-X}In_XSb$
1	0	1330
2	0.1	1276.8
3	0.15	1250.2
4	0.2	1223.6
5	0.25	1197.0
6	0.3	1170.4
7	0.35	1143.8
8	0.4	1117.2
9	0.45	1090.6
10	0.5	1064.0

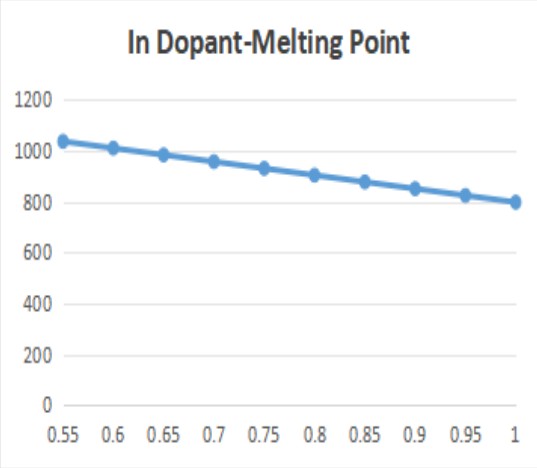
Table-1: In Doping Concentration x:0.00-0

SI.No	In Dopant Concentration (X)	Melting Point $Al_{1-x}In_xSb$
1	0.55	1037.4 1010.8
2	0.6	984.2
3	0.65	957.6
4	0.7	931,0
5	0.75	904.4
6	0.8	877.8
7	0.85	851.2
8	0.9	824.6
9	0.95	798.0
10	1.00	

Table-2: Indium Dopant Concentration X: 0.55-1.00



Graphical Representation: Indium Dopant (X: 0.50-1.00)



Graphical Representation

Indium Dopant (X: 0.00-0.50)

Thermal Stability: The alloy has a wide melting-point range (798–1064 K), supporting high-quality epitaxial growth. Lattice matching is compatible with substrates like GaSb and InSb for low defect densities. Substrate preparation uses GaSb or InSb wafers for lattice matching. For Surface Treatment, Ultrasonic cleaning and plasma cleaning remove contaminants. For orientation purposes, (100) crystal orientation is preferred for uniform epitaxial growth.

Method. Molecular Beam Epitaxy (MBE) or Metal-Organic Chemical Vapor Deposition (MOCVD) growth parameters: substrate temperature 400–500 °C.

Ultra-high vacuum (~10^{-10} Torr) and Precise control of the Al/In ratio to achieve the desired x in $Al_xIn_{1-x}Sb$. The quantum-well (QW) layer structure consists of $Al_xIn_{1-x}Sb$ quantum wells embedded in AlSb or InSb barriers. A 2D Electron Gas (2DEG)

forms at the heterojunction for spin-qubit operation. As the indium content (x) rises, the melting point falls roughly linearly. This illustrates alloy weakening from increased In, in addition to affecting thermal-processing windows and interface quality in hetero structures. Quantum devices' thermal management, with Pertinence to Quantum Computing, makes it possible to fabricate quantum hetero structures at lower temperatures. It reduces strain from thermal mismatch and helps match substrate properties. Supports sustained cryogenic qubit operation through variable thermal engineering.

Conclusion

As the concentration of Indium (In) rises, the melting point of $Al_{1-x}In_xSb$ falls. This benefits cryogenic system compatibility by enabling the formation of quantum structures (such as wells and quantum dots) at low temperatures. During epitaxial manufacture, the linear reduction in thermal conductivity enables precise control of the heat budget by reducing heat conduction. At 300 K, InSb's thermal conductivity is comparatively modest (~0.18 W/cm·K). Al alloying decreases electron mobility while increasing thermal conductivity. For quantum devices, the trade-off is optimized to dissipate heat while the gate is operating and to steer clear of thermal noise, which causes qubit decoherence. As the concentration of Indium (In) rises, the melting point of $Al_{1-x}In_xSb$ falls.

Phonon interactions and heat capacity influence qubit coherence times. $Al_{1-x}In_xSb$ doping allows customized, reduced phonon scattering in configurations that fit the lattice. The coefficient of Thermal Expansion x can be used to adjust thermal and lattice expansion. Preventing interfacial strain with substrates (such as GaSb and InAs) is crucial. Preserving coherence in hetero structures and quantum wells. $Al_{1-x}In_xSb$ demonstrates thermoelectric potential in quantum thermoelectric devices: locally cooling quantum circuits and harvesting Joule—heating energy in cryogenic settings. Pertinence to Quantum Computing: Thermal characteristics are important for suppressing decoherence, controlling solid-state qubit temperature, growing scalable quantum materials epitaxially, and Enabling High-Fidelity operation of quantum gates.

The topological insulator phase is achieved at specific alloy compositions for Majorana-based qubits. Qubit Implementation: Spin Qubits Use electron spins in $Al_xIn_{1-x}Sb$ quantum dots controlled via gate voltages. Topological qubits use proximity coupling to superconductors (Al, Nb) to generate Majorana fermions. Charge Qubits: Implemented via single-electron transistors (SETs) patterned on the alloy. Device patterning uses Electron

Beam Lithography (EBL) to create nanoscale features.

Etching uses reactive ion etching (RIE) to define qubit islands and gate structures. Gate Metallization uses Deposition of Ti/Au or Al gates for qubit control, depending on the superconducting material choice. Al or Nb thin films are deposited by In-situ sputtering or evaporation to ensure clean interfaces.

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