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Investigation of Temperature-Induced Bandgap Variations in InSb, InAs, and GaAs Semiconductor Nanostructures Based on the Varshni Model

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Abstract - The variation of bandgap energy with temperature plays a crucial role in determining the behavior and efficiency of semiconductor nanostructures used in electronic and optoelectronic systems. In this work, a theoretical analysis is carried out on InSb, InAs, and GaAs nanostructures by applying the Varshni relation to describe the change in bandgap energy over a temperature interval of 0 K–600 K. The analysis indicates that InSb shows the strongest response to temperature variation, which makes it particularly valuable for applications such as infrared sensing and thermal imaging technologies. InAs demonstrates a moderate level of temperature dependence, supporting its use in high-speed electronic devices and infrared photodetectors. In contrast, GaAs maintains relatively stable bandgap characteristics across the temperature range, making it well suited for optoelectronic devices including light-emitting diodes, laser diodes, and solar cells. Overall, the results establish a quantitative basis for selecting appropriate semiconductor materials for devices operating under different thermal conditions. Furthermore, the Varshni model provides an effective theoretical approach for predicting and interpreting temperature-induced changes in bandgap energy in modern semiconductor technologies.

Keywords: Semiconductor nanostructures, bandgap engineering, Varshni equation, temperature dependence, InSb, InAs, GaAs, optoelectronic devices.

1. INTRODUCTION

Semiconductor materials form the backbone of contemporary electronic and photonic technologies because their electrical and optical behavior can be deliberately tailored through band structure engineering. A key parameter governing these properties is the bandgap energy, which strongly influences the electronic configuration, optical absorption processes, emission wavelengths, and the transport of charge carriers within a material. The bandgap is defined as the energy separation between the valence band and the conduction band and represents the minimum energy needed to promote an electron into the conduction band, where it can contribute to electrical conduction [1]

Among the most important semiconductor systems are the III–V compound materials, including indium antimonide (InSb), indium arsenide (InAs), and gallium arsenide (GaAs). These semiconductors are widely employed in advanced electronic and optoelectronic technologies because they possess direct bandgap structures and relatively high electron mobility. Such characteristics enable efficient light emission, rapid carrier transport, and high-frequency operation [2][3] As a result, these materials play a major role in devices such as infrared detectors, microwave components, high-speed transistors, and photonic integrated circuits [4]. InSb and InAs belong to the class of narrow-bandgap semiconductors, which makes them highly effective for long-wavelength infrared sensing. In contrast, GaAs has a comparatively wider bandgap and is commonly used in optoelectronic devices including semiconductor lasers, light-emitting diodes, and high-frequency electronic systems [5][6]

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The advancement of nanotechnology has further expanded the capabilities of semiconductor materials through the development of nanostructured systems such as quantum wells, nanowires, and quantum dots. At nanometer length scales, the phenomenon of quantum confinement alters the electronic and optical characteristics of semiconductors, leading to modified band structures and tunable bandgap energies. These changes can significantly enhance device functionality and efficiency [7][8] Nanostructures based on InSb, InAs, and GaAs are therefore attracting considerable attention for emerging applications in nanoelectronics and nanophotonics, including quantum information devices, nanoscale lasers, and high-sensitivity photodetectors [9][10]

Temperature is one of the most influential external factors affecting the band structure of semiconductor materials. With increasing temperature, atomic vibrations within the crystal lattice become more intense, causing lattice expansion and stronger electron–phonon interactions. These processes generally lead to a decrease in the bandgap energy. Such temperature-dependent changes can alter important device characteristics, including emission wavelength, carrier mobility, and overall operational efficiency [11]. Consequently, understanding how temperature modifies the bandgap is essential for predicting the behavior of semiconductor devices under practical operating conditions [12]

To describe the relationship between temperature and bandgap energy, several theoretical formulations have been proposed. One of the most widely adopted empirical expressions is the Varshni equation, which provides an accurate description of bandgap variation over a broad temperature range [13]. The equation incorporates material-dependent parameters that account for the combined effects of lattice expansion and electron–phonon coupling. Because of its reliability and simplicity, the Varshni model has been extensively applied to numerous semiconductor systems, including III–V compounds such as GaAs, InAs, and InSb [14]

The influence of temperature becomes even more significant when dealing with semiconductor nanostructures. In nanoscale materials, thermal variations can modify the degree of quantum confinement and affect carrier dynamics. Even small shifts in bandgap energy may produce noticeable changes in optical emission, absorption behavior, and electronic transport properties, thereby impacting device stability and performance. Understanding these effects is therefore crucial for the reliable design of nanoscale optoelectronic systems

Although the temperature dependence of semiconductor bandgaps has been widely investigated, comparative theoretical analyses focusing on InSb, InAs, and GaAs nanostructures remain valuable for evaluating their suitability in temperature-sensitive applications. These materials possess different intrinsic bandgap energies and temperature coefficients, making them appropriate candidates for examining thermal effects in semiconductor nanodevices [15]

In view of this, the present work conducts a theoretical analysis of the temperature-dependent bandgap energies of InSb, InAs, and GaAs semiconductor nanostructures using the Varshni model. The study examines how the bandgap of each material evolves over a wide temperature range and compares their thermal responses. Furthermore, the relevance of these results to practical applications such as infrared detection systems, high-speed electronic components, and optoelectronic devices is also discussed.

2. THEORETICAL FRAMEWORK

2.1 Energy Band Structure of Semiconductors

The band structure of a semiconductor describes the arrangement of permissible and forbidden energy states available to electrons within a crystalline solid. This electronic structure largely determines how charge carriers behave in the material and therefore influences properties such as electrical conductivity, optical absorption, carrier mobility, and the effectiveness of the material in electronic and optoelectronic technologies. For semiconductors like Indium Antimonide (InSb), Indium Arsenide (InAs), and Gallium Arsenide (GaAs), the band structure is particularly important because it governs their performance in a wide range of device applications. These materials belong to the group of III–V compound semiconductors and are known for having a direct bandgap.

In a direct bandgap material, the lowest point of the conduction band and the highest point of the valence band occur at the same momentum position in the Brillouin zone, as illustrated in Figure 1. This alignment allows electrons to recombine directly with holes while emitting photons, making such materials highly efficient for

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light generation and detection. Consequently, III–V semiconductors are widely used in light-emitting devices, photodetectors, and high-speed electronic components. Among these materials, Indium Antimonide (InSb) is characterized by an extremely small bandgap, approximately 0.17 eV at room temperature. Indium Arsenide (InAs) also exhibits a direct and relatively narrow bandgap, about 0.36 eV at room temperature. In contrast, Gallium Arsenide (GaAs) possesses a significantly larger direct bandgap, approximately 1.42 eV at room temperature.

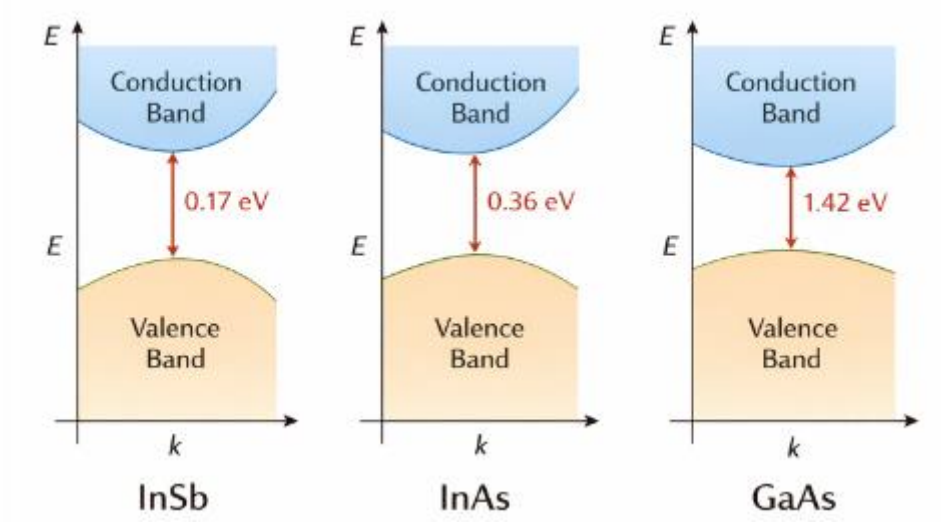

Figure 1: The band structure of InSb, InAs and GaAs semiconductors

2.2 Varshni Model for Temperature Dependence of Bandgap

The Varshni relation therefore serves as an effective theoretical framework for estimating temperature-related bandgap variations in semiconductors and can assist in the development of reliable and high-performance electronic and optoelectronic devices. This model relates bandgap energy to temperature through two material-dependent parameters expressed as:

$$E(T) = E_g(0) - \frac{\alpha T^2}{T + B} \qquad (1)$$

where:

- $E(T)$ = bandgap at temperature T
- $E(0)$ = bandgap at 0 K
- α, B = material-dependent constants
- T = absolute temperature (K)g

The parameters α and β characterize the strength of electron–phonon interactions and lattice expansion effects in the semiconductor.

3. Materials and Methods

A theoretical modeling framework was adopted to examine how temperature influences the bandgap energies of InSb, InAs, and GaAs semiconductor nanostructures. These materials belong to the group of III–V compound semiconductors and are known for their well-documented temperature-dependent electronic characteristics. To represent the relationship between bandgap energy and temperature, the analysis was carried out using the Varshni relation, which accounts for the nonlinear behavior of bandgap variation as temperature changes. The material-specific constants required for the calculations were obtained from reliable literature sources and are summarized in Table 1. Using these parameters, bandgap values were calculated over the selected temperature range, and the resulting bandgap–temperature trends were analyzed to compare the thermal response and stability of the three semiconductor materials.

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Table 1: Varshni Equation Parameters for InSb, InAs and GaAs

Material	$E_g(0)$ (eV)	α (meV/K)	β (K)
InSb	0.235	0.32	106
InAs	0.417	0.276	93
GaAs	1.519	0.5405	204

4. Results and Discussion

The Figure 2 presents the relationship between temperature and bandgap energy for the semiconductor nanostructures InSb, InAs, and GaAs, obtained through calculations based on the Varshni model. The results indicate that the bandgap energy of each material gradually declines as temperature rises. This reduction follows a nonlinear trend, which can be attributed to the influence of crystal lattice expansion at higher temperatures as well as increased interactions between charge carriers and lattice vibrations (phonons).

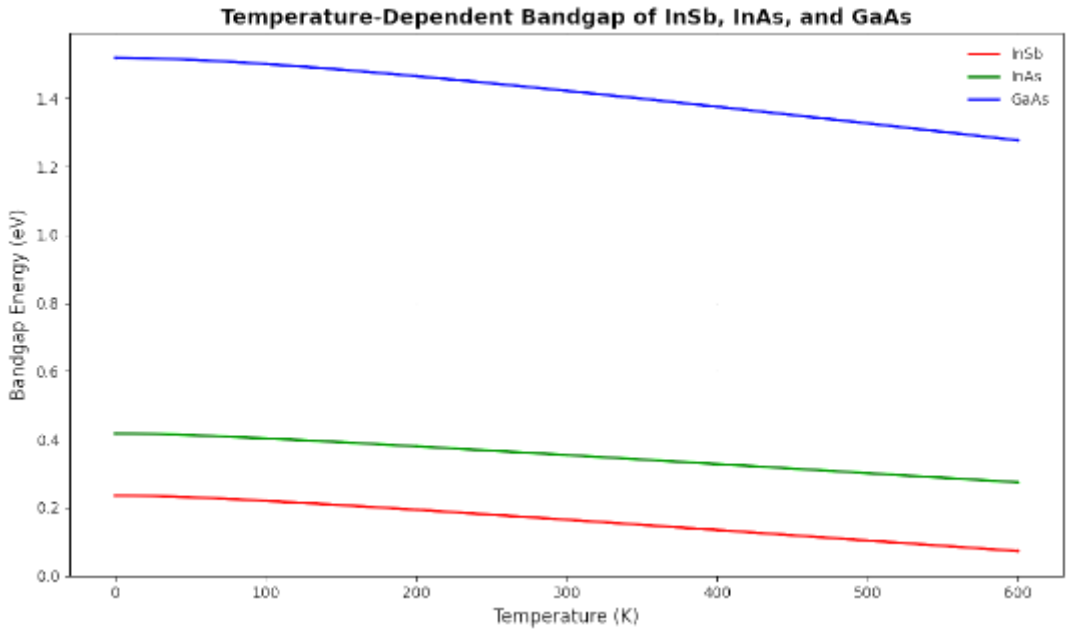

Figure 2: Bandgap energy versus temperature for the InSb, InAs, and GaAs semiconductor nanostructures

The red curve representing InSb shows the most pronounced reduction in bandgap energy as temperature rises, revealing that this material is highly responsive to thermal changes. Such behavior makes InSb particularly useful in infrared sensing and thermal imaging systems that operate within low to intermediate temperature

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ranges, where accurate spectral detection is required. Nevertheless, at higher temperatures, the substantial narrowing of the bandgap may limit its efficiency and device stability.

For InAs, indicated by the green curve, the bandgap decreases at a more moderate rate with increasing temperature. This intermediate response suggests a reasonable balance between temperature sensitivity and electronic stability. Because of this property, InAs is well suited for applications such as high-speed transistors, infrared photodetectors, and other optoelectronic components that must function reliably under moderate thermal conditions.

In contrast, the blue curve corresponding to GaAs shows only a slight variation in bandgap energy across the examined temperature range. This relatively small change reflects strong thermal stability, a feature that is particularly advantageous in devices that demand consistent electrical and optical performance. Consequently, GaAs is widely employed in technologies such as light-emitting diodes, semiconductor lasers, photovoltaic devices, and high-frequency electronic circuits.

Taken together, the trends illustrated in the Figure 2 highlight the importance of selecting semiconductor materials according to the thermal demands of specific device applications. InSb is best suited for highly temperature-responsive infrared systems, InAs offers a balanced performance for fast electronic and optoelectronic devices, while GaAs provides the stability required for thermally robust optoelectronic technologies, as indicated by the labeled curves in the Figure 3.

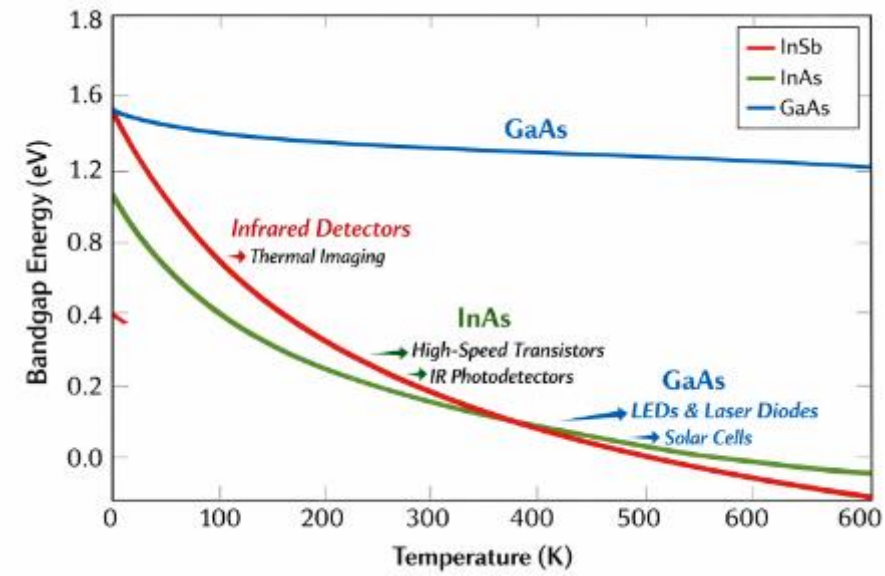

Figure 3: Labeled curves of bandgap energy versus temperature for the InSb, InAs, and GaAs semiconductor nanostructures

5. CONCLUSION

The theoretical analysis carried out in this work shows that the bandgap energies of InSb, InAs, and GaAs semiconductor nanostructures decrease in a nonlinear manner as temperature increases, consistent with the behavior described by the Varshni model. Among the three materials, InSb exhibits the strongest dependence on temperature, indicating a high degree of thermal sensitivity. This property makes it particularly suitable for infrared sensing and thermal imaging applications operating at low to intermediate temperatures, although effective temperature control becomes necessary at higher operating conditions. InAs, on the other hand, displays a moderate change in bandgap with temperature. This intermediate response provides a balance between sensitivity and stability, which supports its use in devices such as high-speed transistors and infrared photodetectors that must maintain reliable performance over a reasonably broad temperature range. GaAs shows the smallest variation in bandgap energy with increasing temperature, reflecting a high level of thermal stability. This characteristic makes it well suited for optoelectronic technologies that require stable emission and electronic behavior, including light-emitting diodes, semiconductor lasers, and photovoltaic systems. Overall, the results highlight the importance of considering temperature effects when selecting semiconductor materials

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for device applications. By understanding how the bandgap of each material responds to temperature changes, engineers and researchers can choose materials that best match the thermal conditions of a given application.

REFERENCES

[1]. Adachi, S. (2005). *Properties of Semiconductor Alloys: Group-IV, III–V and II–VI Semiconductors.*
[2]. Arakawa, Y., & Sakaki, H. (1982). Multidimensional quantum well laser and temperature dependence.
[3]. Bimberg, D., Grundmann, M., & Ledentsov, N. (1999). *Quantum Dot Heterostructures.*
[4]. Blakemore, J. S. (1982). Semiconducting and other major properties of GaAs.
[5]. Harrison, P. (2016). *Quantum Wells, Wires and Dots.*
[6]. Michler, P. (2017). *Quantum Dots for Quantum Information Technologies.*
[7]. Pässler, R. (1999). Parameter sets due to fitting of the temperature dependencies of semiconductor band gaps.
[8]. Pässler, R. (2003). Temperature dependence of semiconductor band gaps.
[9]. Rogalski, A. (2011). Infrared detectors: status and trends.
[10]. Singh, J. (2012). *Semiconductor Devices: Basic Principles.*
[11]. Streetman, B., & Banerjee, S. (2006). *Solid State Electronic Devices.*
[12]. Sze, S. M., & Ng, K. (2007). *Physics of Semiconductor Devices.*
[13]. Varshni, Y. P. (1967). Temperature dependence of the energy gap in semiconductors.
[14]. Vurgaftman, I., Meyer, J., & Ram-Mohan, L. (2001). Band parameters for III–V compound semiconductors.
[15]. Yu, P., & Cardona, M. (2010). *Fundamentals of Semiconductors.*