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INFLUENCE OF LINEAR DOPING PROFILES ON THE ELECTROPHYSICAL FEATURES OF p-n JUNCTIONS

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This study investigated the impact of linear graded doping concentrations on the electrophysical properties of p-n junctions based on Si and GaAs. Doping gradients ranged from $1{\cdot}10^{16}$ to $1{\cdot}10^{20}$ cm^{-4}, and the analysis was performed at temperatures between 200 K and 500 K, in 100 K increments. The Poisson equation was solved for linear doping profiles, with analytical solutions derived for both Si and GaAs materials. These solutions provided detailed insights into the electric field, potential distributions, built-in potential, and the width of the depletion region. For both materials, the built-in potential was temperature-dependent, with Si exhibiting a more significant variation due to its higher intrinsic carrier concentration. The depletion region width was influenced by both doping concentration and temperature, with GaAs showing a more pronounced variation in width, owing to its distinct material properties compared to Si. The results highlight the crucial role of doping gradients and temperature variations in shaping the performance of the linear graded p-n junctions, offering valuable implications for the design of semiconductor devices such as diodes and transistors optimized for different temperature conditions.
Keywords: *Linear graded p-n junction; Built-in potential; Electrostatic properties; Linear graded doping; Cryogenic temperatures*
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INTRODUCTION

Although research on new materials for semiconductor electronic devices is expanding, silicon (Si) and gallium arsenide (GaAs) remain dominant in practical applications [1-4]. Consequently, the study of the electrostatic properties of these materials continues to be a crucial area of research [5-7]. The p-n junction, a fundamental component in semiconductor devices made from Si and GaAs, plays a pivotal role in current transfer, electrostatic characteristics, and the operation of devices across a broad range of power and temperature conditions. The performance of these devices is intricately linked to a comprehensive understanding of the operating principles of the p-n junction and the external factors that influence it [8-9]. These factors include the effects of incomplete ionization at low temperatures [10-11], the influence of geometric size [12], and other related phenomena [13].

One of the key factors affecting the behavior of p-n junctions is the doping profile, which governs the electric field and the carrier dynamics within the junction. Specifically, the impact of non-uniform doping concentration profiles on the operation of p-n junctions has been underexplored both analytically and experimentally. Traditionally, p-n junctions have been studied with uniform or step-function doping profiles; however, these idealized models do not always capture the complexities of real-world devices, particularly those operating under extreme conditions. Experimental studies [14-18] suggest that non-uniform doping profiles, such as linear grading, can significantly influence the electrostatic properties and overall performance of p-n junctions. Nevertheless, this area remains insufficiently investigated and warrants more in-depth analysis.

Linear graded p-n junctions, in which the doping concentration varies gradually and linearly across the junction, offer distinct advantages over both uniform and non-uniform doping profiles [19]. In these junctions, the gradual transition between the p-type and n-type regions results in a more uniform built-in electric field, which reduces carrier recombination and improves charge carrier collection efficiency [20-23]. This characteristic makes linear graded p-n junctions particularly beneficial for applications such as solar cells, photodetectors, light-emitting diodes (LEDs), and power devices, where efficiency and performance are closely tied to the smooth distribution of charge carriers. Moreover, the gradual change in doping concentration can lower the breakdown voltage, enhance device reliability, and improve high-speed performance.

However, the theoretical understanding of the electrostatic properties of linear graded p-n junctions, particularly regarding their temperature dependence, remains limited. To address this gap, this article focuses on the analytical investigation of the electrostatic properties of linear graded p-n junctions made from Si and GaAs, studied over a wide temperature range. By examining the effects of linear grading on the electric field, potential distribution, and depletion region, this research aims to provide a deeper understanding of how doping profiles influence device performance. Additionally, this study will explore how external factors, such as temperature and geometric size, interact with the doping profile to affect the behavior of p-n junctions in real-world applications. The insights gained from this research could lead to improved design strategies for a variety of semiconductor devices, particularly in environments where high efficiency, reduced recombination, and stable operation over temperature are crucial.

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MATERIAL AND METHODS

In fact, p-n junctions are formed by combining p-type and n-type semiconductors through processes like diffusion, ion implantation, epitaxial growth, or alloying, with precise control of doping and structure quality. The junction's unique properties arise from the depletion region created by carrier recombination, enabling applications in forward and reverse bias modes, including advanced structures like radial and heterojunctions. Uniform doping profiles are formed by evenly distributing dopants through methods like ion implantation or epitaxial growth, ensuring consistent electrical properties. Nonuniform profiles are created by varying dopant concentration using graded diffusion or selective implantation, enabling tailored device performance. As highlighted in the Introduction, this article addresses the problem of p-n junctions with non-uniform doping concentrations, which have not been extensively studied.

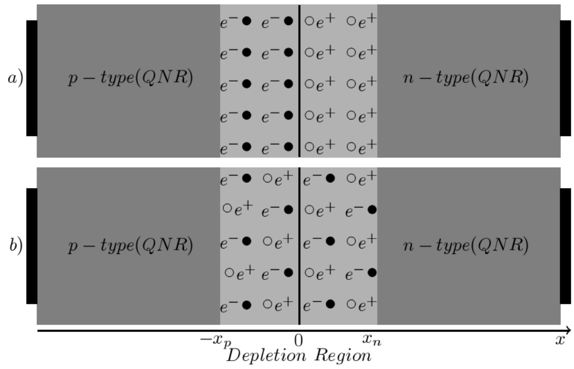

Figure 1. Schematic representation of a 2D cross-section of the modeled planar p-n junction:
a) uniform doping profile, and b) non-uniform doping profile

Figure 1 illustrates a planar p-n junction with: a) a uniform doping profile, and b) a non-uniform doping profile, highlighting distinct characteristics in current transfer mechanisms and electrostatic distributions between the two cases. The depletion region extends from $-x_p$ to x_n, with its width denoted as W, linear graded p-n junction specific to the junction structure and as expressed: $\left|-x_p\right| = \left|-\frac{W}{2}\right| = x_n = \frac{W}{2}$. To identify these unique properties, it is essential to solve the Poisson equation for each specific case. To simplify finding solutions, approximations are applied, but only for the low injection case. The Poisson equation for the low injection case is written as equation (1).

$$\frac{dE(x)}{dx} = -\frac{d^2\varphi(x)}{dx^2} = \frac{q}{\varepsilon\varepsilon_0}\cdot\left(N_D(x) - N_A(x)\right). \tag{1}$$

Where $E(r)$ represents the electric field, ε denotes the permittivity of the semiconductor material, for Si ε is 11.9, for GaAs ε is 12.9, $\varepsilon_0 = 8.85\cdot10^{-12}$ F·m^{-1} vacuum permittivity. The linear doping profile can be represented as (2):

$$N_D(x) - N_A(x) = a\cdot x \tag{2}$$

If the width of the depletion region is non-uniform, as in case b), the acceptor doping concentrations $N_A\left(x\right)$ and donor doping concentrations $N_D\left(x\right)$ are expressed qualitatively as functions of distance. a is the doping gradient. These expressions are solved together under boundary conditions $E(-x_p) = 0$ and $E(x_n) = 0$, for the depletion region, the distribution of the electric field is given by equation (3a), while for other regions, the electric field distribution is described by equation (3b).

$$E(-x_p < x < x_n) = \frac{q\cdot a}{2\varepsilon\varepsilon_0}\cdot\left(x^2 - \left(x_n\right)^2\right), \tag{3a}$$

$$E(x \le -x_p,\ x_n \ge x) = 0\,. \tag{3b}$$

Along with the electric field distribution, it is also important to determine the electrostatic potential distribution. Using the following expression $\varphi(x) = -\int E(x)dx$ and $\varphi(x \le -x_p) = 0$, $\varphi(x \ge x_n) = \varphi_{bi}(T) - U_{p-n}$ initial conditions, the electrostatic potential is obtained from expression (4). The built-in potential is represented by $\varphi_{bi}(T)$, and the external source voltage is represented by U_{p-n}.

$$\varphi(-x_p < x < x_n) = \frac{q\cdot a}{6\varepsilon\varepsilon_0}\cdot\left(x^3 - 3x_n^2\cdot x\right). \tag{4}$$

Using the selected initial conditions, the width of the depletion region was determined and is expressed by equation (5). From equation (5), it can be seen that the width of the depletion region depends on temperature, built-in potential, and the doping gradient.

$$W=\sqrt[3]{\frac{24\varepsilon\varepsilon_0}{q\cdot a}\cdot\left(\varphi_{bi}(T)-U_{p-n}\right)}\,. \tag{5}$$

Another important parameter is the built-in potential, expressed by equation (6) for a linearly graded doping concentration in a p-n junction.

$$\varphi_{bi}(T)=\frac{2kT}{q}\cdot\ln\left(\frac{a\cdot x_n}{n_i(T)}\right). \tag{6}$$

Where k is the Boltzmann constant, T is the temperature, q is the charge of an electron, $n_i(T)$ is the intrinsic carrier concentration of the semiconductor. At 300 K (room temperature), the intrinsic carrier concentration of Si is approximately $n_i(300)=1.5\cdot10^{10}\ cm^{-3}$, for GaAs approximately $n_i(300)=1.7\cdot10^{6}\ cm^{-3}$. The results derived from the above analytical expressions are presented and analyzed in the "Results and Discussion" section.

RESULTS AND DISCUSSION

The results presented and analyzed in this section correspond to temperatures ranging from 200 K to 500 K in 100 K increments, with a doping gradient spanning from $1\cdot10^{16}\ cm^{-4}$ to $1\cdot10^{20}\ cm^{-4}$. In Figure 2, the width of the depletion region of a linearly graded p-n junction made of Si material depends on the doping gradient at different temperatures.

In silicon (Si), the doping gradient remains largely unchanged as temperature increases from 200K to 500K. However, the carrier concentration increases with temperature, affecting the material's conductivity and recombination rates. The depletion region width decreases linearly with increasing doping concentration, as a higher doping concentration strengthens the electric field, reducing the width of the depletion region. Gallium Arsenide (GaAs) is a high-performance semiconductor with a direct bandgap of 1.42 eV, making it ideal for optoelectronic applications like LEDs and laser diodes. It has high electron mobility, which enables fast switching in high-speed electronics, but lower thermal conductivity than silicon. GaAs is widely used in high-frequency devices, such as radar and satellite communications, but its higher cost and fabrication complexity limit its use compared to silicon. In Figure 3, the width of the depletion region of a linearly graded p-n junction made of GaAs material depends on the doping gradient at different temperatures.

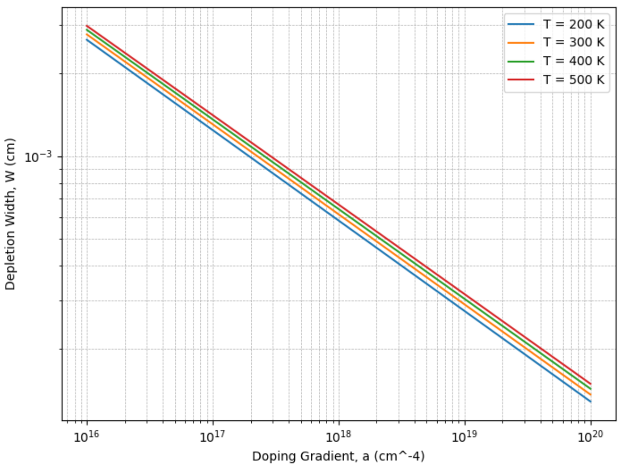

Figure 2. The width of the depletion region in a linearly graded p-n junction based on Si as a function of the doping gradient at different temperatures

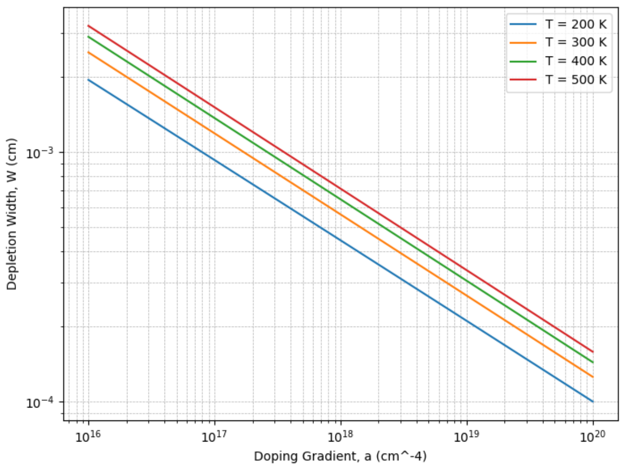

Figure 3. The width of the depletion region in a linearly graded p-n junction based on GaAs as a function of the doping gradient at different temperatures

Compared to Si, GaAs undergoes more significant changes as the temperature increases from 200 K to 500 K. In both materials, the depletion region width decreases linearly with increasing doping concentration. In Si, the depletion region width changed from 22 µm to 5.8 µm, while in GaAs, it changed from 83.4 µm to 0.833 µm. At 200 K, the depletion region width changes from 22 µm for $1\cdot10^{16}\ cm^{-4}$ to 5.8 µm for $1\cdot10^{20}\ cm^{-4}$. As temperature increases, the width decreases further, with similar trends observed at 300K, 400K, and 500K, showing a more pronounced reduction with higher doping concentrations.

Figure 4 demonstrates that the built-in potential of a linearly graded p-n junction based on GaAs increases consistently with both temperature and doping concentration. At 200 K, the built-in potential ranges from 1.187 V to 1.23 V. At 300 K, it increases to a range of 1.2187 V to 1.46 V. At 400 K, the range shifts to 1.387 V to 1.653 V, and at

500K, it varies between 1.527 V and 1.86 V. This trend clearly indicates a consistent increase in the built-in potential with rising temperature and doping concentration. Similarly, the width of the depletion region in the Si-based linearly graded p-n junction decreases as the doping gradient increases from $1 \cdot 10^{16}\ cm^{-4}$ to $1 \cdot 10^{20}\ cm^{-4}$ across temperatures ranging from 200K to 500K. As temperature increases, the width decreases further, with similar trends observed at 300K, 400K, and 500K, showing a more pronounced reduction with higher doping concentrations. Figure 5 illustrates that the built-in potential of a linearly graded p-n junction based on Si increases with both temperature and doping concentration. At 200K, the built-in potential ranges from 0.78 V to 0.923 V. At 300 K, it increases to a range of 0.9321 V to 1.123 V. At 400K, the range extends from 1.038 V to 1.26 V, and at 500 K, it varies between 1.082 V and 1.41 V. This shows a consistent increase with both temperature and doping concentration. Similarly, the width of the depletion region in the GaAs-based linearly graded p-n junction decreases as the doping gradient increases from $1 \cdot 10^{16}\ cm^{-4}$ to $1 \cdot 10^{20}\ cm^{-4}$, across temperatures ranging from 200K to 500K.

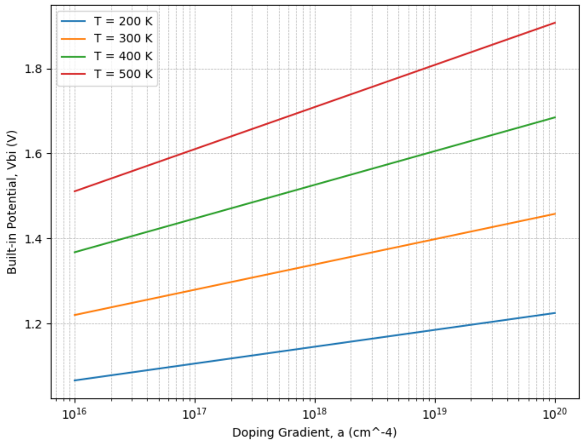

Figure 4. The built-in potential of a linearly graded p-n junction based on GaAs as a function of the doping gradient at different temperatures

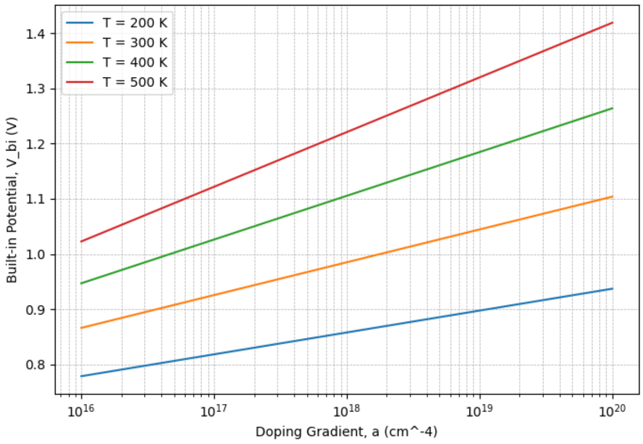

Figure 5. The built-in potential of a linearly graded p-n junction based on Si as a function of the doping gradient at different temperatures

For GaAs, the impact of the doping gradient on the depletion region width is more prominent at higher doping concentrations compared to Si. Across the temperature range of 200 K to 500 K, the depletion region width exhibits significant variation, with more substantial changes occurring at higher doping gradients. At low doping concentrations, the temperature dependence is relatively minor, whereas at high doping concentrations, the depletion width decreases sharply with increasing temperature, demonstrating a more pronounced effect than in Si. This highlights GaAs's greater sensitivity to both temperature and doping concentration, particularly at elevated doping gradients. The built-in potential of the GaAs-based junctions increases consistently with both doping concentration and temperature, ranging from 1.187 V at 200K to 1.86V at 500K for doping concentrations between $1 \cdot 10^{16}\ cm^{-4}$ and $1 \cdot 10^{20}\ cm^{-4}$. In comparison, the built-in potential for Si-based junctions ranges from 0.78V to 1.41V across the same temperature and doping concentration range. Additionally, the width of the depletion region in both materials decreases with increasing doping concentration, but this effect is much more pronounced in GaAs, with changes from 83.4 μm to 0.833 μm at temperatures ranging from 200K to 500K. In contrast, Si shows smaller variations, with the depletion width changing from 22 μm to 5.8 μm over the same temperature range.

CONCLUSIONS

In conclusion, this study provides a comprehensive analysis of the electrostatic properties of linearly graded p-n junctions based on Si and GaAs, with a focus on the effects of doping gradients and temperature variations. The results reveal distinct behaviors between GaAs and Si, with GaAs exhibiting a more pronounced dependence on temperature and doping concentration. At higher doping concentrations, GaAs shows a more significant reduction in the depletion region width with increasing temperature, highlighting its greater sensitivity compared to Si. This behavior underscores GaAs's heightened sensitivity to temperature fluctuations and doping gradients, especially at high doping levels.

The study emphasizes the pivotal role of doping gradients and temperature in shaping the electrostatic properties of p-n junctions. GaAs, with its superior electron mobility and direct bandgap, offers enhanced performance for high-frequency and optoelectronic applications. However, its increased sensitivity to temperature and doping concentration presents both challenges and opportunities for device optimization. In contrast, Si remains more stable with respect to temperature changes, making it a more predictable material, but it may not achieve the same performance levels in specialized applications. These findings are crucial for the design of semiconductor devices, particularly in applications where efficiency, reduced recombination, and stable operation across varying temperatures are critical. The insights gained can inform the optimization of p-n junctions for a range of devices, such as LEDs, photodetectors, and power devices, ensuring improved performance and reliability in diverse operating environments.

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ВПЛИВ ЛІНІЙНИХ ПРОФІЛІВ ЛЕГУВАННЯ НА ЕЛЕКТРОФІЗИЧНІ ОСОБЛИВОСТІ P-N-ПЕРЕХОДІВ

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У цій роботі досліджено вплив лінійного градієнта концентрації легування на електрофізичні властивості p-n переходів на основі Si і GaAs. Градієнти легування становили від $1\cdot10^{16}$ до $1\cdot10^{20}$ см$^{-4}$, а аналіз проводили при температурах від 200 K до 500 K з кроком 100 K. Рівняння Пуассона було розв'язане для лінійних профілів легування, а аналітичні рішення отримані для матеріалів Si і GaAs. Ці розв'язки дали детальне уявлення про електричне поле, розподіл потенціалів, вбудований потенціал і ширину області виснаження. Для обох матеріалів вбудований потенціал залежав від температури, причому Si демонстрував більш значну зміну через вищу концентрацію власних носіїв. На ширину області збіднення впливають як концентрація легування, так і температура, причому GaAs демонструє більш виражену варіацію ширини, що пояснюється його відмінними властивостями порівняно з Si. Отримані результати підкреслюють вирішальну роль градієнтів легування і температурних варіацій у формуванні характеристик лінійних градуйованих p-n переходів, пропонуючи цінні висновки для проектування напівпровідникових приладів, таких як діоди і транзистори, оптимізованих для різних температурних умов.

Ключові слова: *лінійний градуйований p-n перехід; вбудований потенціал; електростатичні властивості; лінійне градуйоване легування; кріогенні температури*