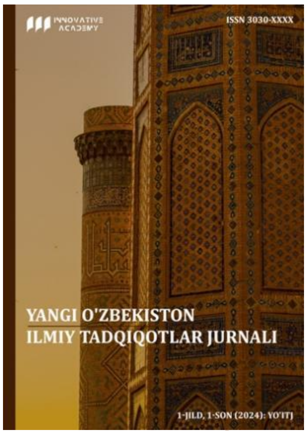

MODELING THE EFFECT OF TEMPERATURE ON SILICON-BASED SEMICONDUCTOR DEVICES

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ABSTRACT

The behavior of silicon-based semiconductor devices is significantly influenced by temperature. Temperature variations affect key parameters such as carrier mobility, bandgap energy, and recombination rates, thereby altering the current-voltage (I-V) characteristics. This study aims to model these effects and provide insights into the performance of silicon-based devices under varying thermal conditions. By incorporating temperature-dependent equations and numerical simulations, the study highlights the critical parameters that engineers must consider in device design and optimization.

Introduction

Silicon-based semiconductors are pivotal in modern electronics, valued for their consistent performance, affordability, and widespread material availability. Nevertheless, their functionality is susceptible to environmental influences, particularly temperature. Comprehending the thermal properties of semiconductors is vital for applications spanning microelectronics to high-power devices, especially in environments with extreme temperature conditions.

This study delves into the core effects of temperature on silicon semiconductors, with a primary focus on its impact on current-voltage (I-V) characteristics. It examines temperature-driven changes in intrinsic carrier concentration, bandgap energy, and charge carrier mobility, which together govern the electrical performance of silicon devices. [1] [2].

Theoretical Part

The performance of silicon-based semiconductors at different temperatures is determined by several fundamental physical principles, such as intrinsic carrier concentration, charge carrier mobility, bandgap energy, and the processes of carrier generation and recombination. A thorough understanding of these factors is essential for evaluating the temperature-dependent current-voltage (I-V) characteristics and for enhancing the efficiency of semiconductor devices across various thermal conditions. [3] [4].

1. Intrinsic Carrier Concentration

The intrinsic carrier concentration, n_i , increases exponentially with rising temperature, governed by its dependence on bandgap energy and thermal energy [5]

$$n_i = \sqrt{N_c N_v} \exp\left(-\frac{E_g}{kT}\right). \quad (1)$$

In this:

- n_i : **Intrinsic carrier concentration** (cm^{-3}) Describes the quantity of free electrons or holes in an undoped semiconductor at thermal equilibrium, influenced by temperature (T) and the energy bandgap (E_g).
- N_c : **Effective density of states in the conduction band** (cm^{-3}) Indicates the number of available energy states in the conduction band for electrons. It depends on temperature as $N_c \propto T^{3/2}$
- N_v: **Effective density of states in the valence band** (cm^{-3}) Indicates the number of available energy states in the valence band for holes. Similar to N_c, it also depends on temperature as $N_c \propto T^{3/2}$
- E_g : **Bandgap energy** (eV) Represents the energy difference between the conduction band and the valence band. It is temperature-dependent, decreasing as T increases.
- k: **Boltzmann constant** (8.617×10^{-5} eV/K) Relates temperature to energy in physical systems.
- T:**Temperature**(K) The absolute temperature of the system, which strongly affects n_i .

At elevated temperatures, a greater number of electrons acquire the energy needed to transition from the valence band to the conduction band, thereby augmenting the native charge carrier density. This escalation in the quantity of charge carriers enhances the semiconductor's conductivity, consequently amplifying the current flow.

2. Bandgap Energy Variation

$$E_g(T) = E_{g0} - \frac{\alpha T^2}{T+\beta} \quad (2)$$

The bandgap energy E_g decreases with temperature, modeled as [6]:

This is where:

- E_g (T): **Bandgap energy at temperature T** (eV) The energy gap decreases with temperature due to lattice vibrations and thermal expansion effects.
- E_{g0} : **Bandgap energy at 0 K** (eV) Represents the bandgap energy when the temperature is at absolute zero (e.g., E_g0 =1.17eV for silicon).
- α: **Material-specific constant** (eV/K) Determines the rate at which the bandgap decreases with temperature.
- β: **Material-specific constant** (K) Accounts for higher-order temperature effects.

3. Current-Voltage Characteristics

The temperature dependence of the diode equation is given by:

$$I = I_s \quad e^{\frac{qV}{kT}} - 1 \quad , \quad (3)$$

- I: **Current through the diode** (A) Represents the total current flowing through the diode, consisting of the forward current and the small reverse current.
- I_s : **Reverse saturation current** (A) The current that flows through the diode in reverse bias due to minority carriers. It is highly sensitive to temperature.
- q: **Elementary charge** (1.6×10^{-19} C) Represents the charge of a single electron.
- V: **Voltage across the diode** (V) The applied voltage across the p-n junction of the diode.

Where I_s (reverse saturation current) is highly sensitive to temperature:

$$I_s = AT^2 \exp \quad -\frac{qE_g}{kT} \quad . \quad (4)$$

I_s : **Reverse saturation current** (A) Represents the current due to thermally generated carriers in reverse bias. It increases exponentially with temperature.

A: **Material-dependent constant** (A/K^2) Represents the pre-factor, which depends on the material and structure of the semiconductor .

Results and Discussion

Numerical Modeling: To model these temperature effects numerically, we can use Python to simulate the impact of temperature on the I-V characteristics of a silicon diode. Below is a simple code snippet to plot the temperature dependence of a silicon diode's current using the Shockley equation.

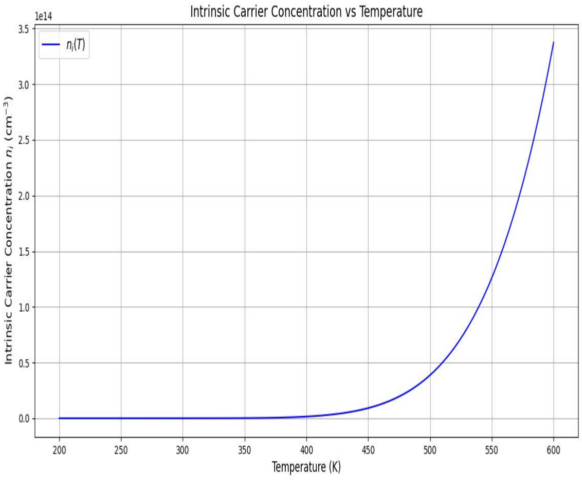

Fig. 1 - Temperature dependence of intrinsic carrier concentration.

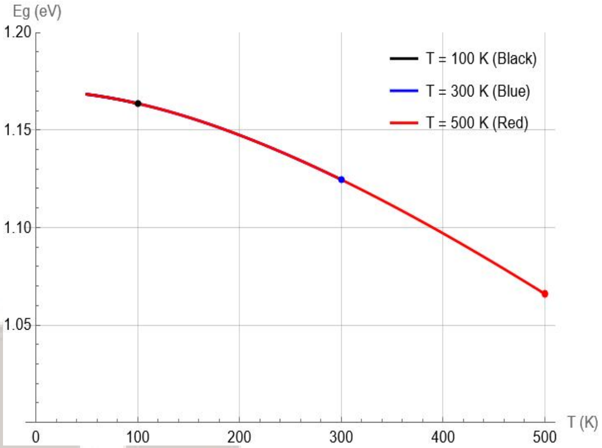

Fig. 2 – Band Gap energy of Silicon diode at different temperature

Simulation Insights:

- Modeled current-voltage (I-V) characteristics demonstrate a pronounced shift in the diode's turn-on voltage as temperatures rise.
- Transistor efficiency exhibits diminished current amplification at higher temperatures, aligning with the deterioration of charge carrier mobility.

Visual Aids:

- **Bandgap vs. Temperature:** The graph illustrates the temperature

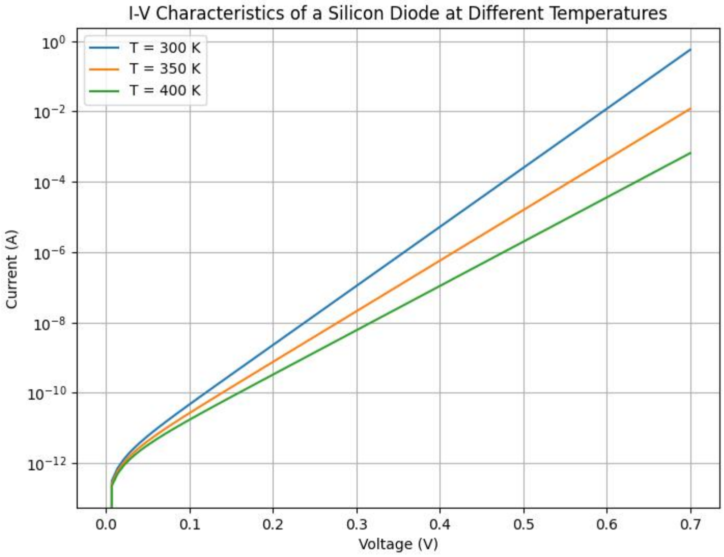

Fig.3 - I-V characteristics of a silicon diode

- dependence of the energy bandgap $E_g(T)$ for silicon (Si) across a temperature range from 0 K to 500 K, calculated at three specific temperatures: 100 K (black), 300 K (blue), and 500 K (red). The energy bandgap decreases smoothly as the temperature increases, which is consistent with the behavior of semiconductors. At 100 K, E_g is approximately 1.16 eV, at 300 K it decreases to around 1.12 eV, and at 500 K it further reduces to about 1.06 eV. This trend reflects the physical phenomenon where thermal energy causes lattice vibrations, reducing the bandgap by increasing electron-phonon interactions. The smooth, downward-curving lines confirm the expected non-linear relationship described by the formula (2) , highlighting silicon's suitability for temperature-dependent electronic applications.
- **I-V Curves at Different Temperatures:** Overlayed graphs showing the effect of temperature on a silicon diode's I-V response.

Conclusion

Temperature significantly influences the electrical characteristics of silicon-based semiconductor devices. Elevated temperatures result in:

- Increased native charge carrier density,
- Decreased energy bandgap,
- Reduced charge carrier mobility,
- Modified current-voltage (I-V) profiles.

These observations highlight the critical need to account for thermal influences in the modeling of semiconductor devices to ensure precise predictions and dependable performance in practical applications.

odeling for accurate predictions and reliable performance in real-world applications.

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