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A UNIFIED MODEL OF SELF-OSCILLATING CURRENT SYSTEMS IN COMPENSATED SILICON AND THE INFLUENCE OF TEMPERATURE AND CONTACT EFFECTS

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Abstract
This paper investigates current self-oscillations in injection structures based on silicon (Si) compensated with Mn, Se, and Zn impurities possessing deep energy levels. A unified physical and mathematical model common to these three different types of impurities is proposed. The influence of potential barriers at the contact interface and temperature on the amplitude and frequency of oscillations is analyzed. The agreement between experimental results and theoretical calculations is explained in terms of the injection–recombination mechanism.

Keywords: Compensated silicon, self-oscillations, injection structure, Mn, Se, and Zn impurities, mathematical model, current–voltage characteristic.

Introduction

In modern microelectronics and nanoelectronics, the investigation of the nonlinear properties of semiconductor materials remains one of the most important research challenges. In particular, self-oscillating current systems observed in compensated silicon offer significant opportunities for the development of novel functional devices. In compensated semiconductors, the close balance between donor and acceptor concentrations leads to complex charge-carrier dynamics. As a result, various nonlinear effects arise within the system, including recombination waves and spontaneous current self-oscillations.

Previous studies have mainly been based on experimental observations, while a unified theoretical model capable of comprehensively explaining the underlying physical mechanisms has not yet been sufficiently developed. Therefore, the objective of the present work is to develop a comprehensive model describing self-oscillating current systems in compensated silicon.

In semiconductor device physics, the development of materials capable of generating stable current oscillations is an important scientific and technological problem. Unlike conventional oscillatory systems, self-oscillations are particularly significant because they can arise directly from the bulk properties of the semiconductor without the need for external inductive–capacitive circuits. Doping silicon with deep-level impurities such as Mn, Se, and Zn complicates its energy spectrum and, under injection conditions, gives rise to a region of negative differential resistance (NDR), thereby creating favorable conditions for oscillatory behavior.

In this study, a model based on a fluctuation potential landscape resulting from material inhomogeneity is proposed to explain the mechanism of low-frequency current self-oscillations in highly compensated silicon. The proposed model demonstrates good agreement with experimental observations.

Based on the available literature, it can be concluded that the mechanism responsible for the emergence of current self-oscillations, the laws governing the variation of their parameters, and the physics of transitions between different types of self-oscillations observed in the same compensated material have not yet been fully understood. To date, neither the theoretical framework nor the physical mechanism of this phenomenon has been completely clarified. Furthermore, the theoretical interpretation of experimental results from the standpoint of the thermodynamic conditions of the self-oscillatory medium remains an open problem requiring further investigation.

At high electric field strengths and under illumination conditions that produce high conductivity in the sample, the temperature increases due to Joule heating. This temperature rise, in turn, enhances the electrical conductivity through the thermal excitation of holes from localized states into the conduction process.

As a result, Joule heating becomes even more intense, leading to a positive feedback mechanism with an avalanche-like character.

When the applied voltage reaches a sufficiently high value:

• electrons are excited from deep energy levels into the conduction band;

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• free electrons recombine with holes in the valence band;
• the hole concentration and hole lifetime decrease.

Consequently:

• the current decreases sharply;
• the sample begins to cool down.

Subsequently:

• optical recharging processes are initiated;
• the entire process repeats periodically.

Therefore, self-oscillations are generated in the system as a result of this cyclic injection–recombination and thermal feedback mechanism.

II. PHYSICAL MODEL AND RESEARCH OBJECT

As the research object, silicon single crystals compensated with donor and acceptor impurities were selected. In highly compensated semiconductors, the concentration of free charge carriers is significantly lower than the concentration of impurity centers, creating favorable conditions for the emergence of nonlinear electrical phenomena.

The investigated samples are assumed to contain nanoscale clusters formed as a result of the spatially nonuniform distribution of impurity atoms. Such nanoclusters create local potential wells that govern the trapping and release processes of charge carriers. As a consequence, nonstationary current states, particularly self-oscillating current systems, can arise within the sample.

The proposed physical model is based on the assumption that deep-level impurity centers and nanoclusters form a fluctuation potential landscape inside the compensated silicon crystal. Under carrier injection conditions, the dynamic redistribution of charge carriers between these localized states and the conduction band leads to periodic variations in conductivity, thereby generating self-oscillatory behavior.

In this study, the electrical conductivity of compensated silicon, the amplitude and frequency of spontaneous current oscillations, the influence of contact resistance, and the effects of impurity nanoclusters are investigated over the temperature range of 1050–1200°C and under various electric field strengths.

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Diffusion-Based Physical Model

The proposed model is based on the diffusion process of impurity atoms within the silicon crystal lattice. During diffusion, the spatial distribution of impurity atom concentration is described by Fick's second law of diffusion.

Diffusion is the process by which atoms or molecules move from a region of higher concentration to a region of lower concentration. In semiconductor technology, this phenomenon is widely used for introducing impurity atoms into the crystal lattice.

The diffusion flux is determined by the following expression:

$$J = -D\frac{dC}{dx}$$

where:

- J – diffusion flux (mol/m²·s);
- D – diffusion coefficient (m²/s);
- dC/dx – concentration gradient;
- x – spatial coordinate;
- − (negative sign) – indicates that the substance moves from a region of higher concentration toward a region of lower concentration.

The diffusion coefficient is temperature-dependent and is described by the Arrhenius equation:

$$D=D_o\exp\left(-\frac{Ea}{kT}\right)$$

Here, Ea is the activation energy of the diffusion process.

As the temperature increases, the diffusion coefficient rises exponentially, thereby increasing the probability of impurity atom clustering.

In compensated silicon, the concentrations of donor and acceptor impurities are approximately equal:

$$N_D \approx N_A$$

As a result, the number of free charge carriers decreases, and the material exhibits a high-resistivity state.

The net carrier concentration is given by:

$$n_0 = N_D - N_A$$

The degree of compensation is defined as:

$$K = N_A / N_D$$

When $K \to 1$, the system approaches a metastable state, where even small perturbations can significantly affect its electrical properties and contribute to the emergence of nonlinear phenomena, including self-oscillatory behavior.

Mechanism of Nanocluster Formation

At elevated temperatures, impurity atoms migrate through the crystal lattice and accumulate in energetically favorable regions, leading to the formation of nanoclusters.

The primary factors responsible for nanocluster formation include:

• high impurity concentration;
• prolonged diffusion time;
• defects in the crystal lattice;
• internal mechanical stresses.

The resulting nanoclusters create local potential wells within the silicon crystal. These potential wells temporarily trap electrons and subsequently release them through emission processes. As a result, charge carriers undergo both spatial and temporal redistribution.

Under the influence of an electric field, electrons move between neighboring nanoclusters. The processes of electron trapping and release occur with a finite delay, giving rise to nonequilibrium carrier dynamics and time-dependent conductivity variations.

These processes occur through the following sequence:

1. charge accumulation;
2. enhancement of the local electric field;
3. rapid release of trapped electrons;
4. generation of a current pulse.

Since this cycle is repeated periodically, spontaneous current self-oscillations are generated within the system.

The frequency of self-oscillations depends on several factors, including:

• the size of the nanoclusters;
• the density of nanoclusters;
• the diffusion temperature;
• the diffusion time;
• the electric field strength;
• the resistance of the contacts.

Therefore, the oscillatory characteristics of compensated silicon can be controlled by modifying the diffusion conditions, impurity distribution, and electrical operating parameters of the structure.

Proposed Unified Model

The proposed unified model describes current self-oscillations in compensated silicon through the interaction of the following factors:

1. donor–acceptor compensation;
2. impurity nanoclusters;
3. generation–recombination processes;
4. drift–diffusion mechanisms;
5. temperature effects;
6. contact effects.

According to the proposed model, the formation of self-oscillating currents in compensated silicon is associated with impurity atom nanoclusters formed during the diffusion process. These nanoclusters act as centers for electron trapping and emission. The periodic variation of current arises from the combined influence of the potential landscape created by the nanoclusters, the applied electric field, temperature-dependent processes, and contact effects.

The interaction between charge-carrier trapping, thermal activation, carrier emission, and recombination processes produces a nonlinear feedback mechanism that leads to stable self-oscillatory behavior. The characteristic parameters of the oscillations, including their amplitude and frequency, are determined by the properties of the nanoclusters, the degree of compensation, and the external operating conditions.

The proposed model provides a unified physical framework for explaining self-oscillating current systems observed in compensated silicon and enables the interpretation of a wide range of experimental results on the basis of a common physical mechanism.

III. DEVELOPMENT OF THE MATHEMATICAL MODEL

The current density in silicon consists of both drift and diffusion components:

$$J = qn\mu E + qD(\partial n/\partial x)$$

where:

• q – electron charge;

- n – electron concentration;
- μ – carrier mobility;
- D – diffusion coefficient;
- E – electric field strength.

According to the Einstein relation:

$$D = \mu kT/q$$

Experimental studies have shown that compensated silicon exhibits spontaneous current self-oscillations. This phenomenon is associated with the recharging of deep energy levels and the redistribution of the electric field within the material.
Let the occupation probability of trap centers be represented by:

$$f = f(x,t)$$

The temporal evolution of the trap occupation is described by:

$$\partial f/\partial t = c_n n(1 - f) - e_n f$$

where:

- c_n – carrier capture coefficient;
- e_n – emission probability (emission rate).

This equation describes the dynamic balance between carrier capture and emission processes at deep-level trap centers, which play a crucial role in the formation of self-oscillatory current regimes in compensated silicon.

Nonlinear Current Model

When self-oscillations arise, the current density can be represented as

$$J=J_0+\alpha E-\beta E^3+\gamma f$$

This equation gives rise to a region of negative differential resistance (NDR).
If:

$$\frac{dJ}{dE}<0$$

the system becomes unstable and may enter a self-oscillatory regime.
The complete mathematical model is described by the following system of equations:

$$\frac{\partial n}{\partial t}=\frac{1}{q}\frac{\partial J}{\partial x}+G-R$$

$$J=qn\mu E+qD\frac{\partial n}{\partial x}$$

$$\frac{\partial E}{\partial x}=\frac{q}{\varepsilon s}(N_D^+-N_A^-+p-n)$$

$$\frac{\partial f}{\partial t}=c_n n(1-f)-e_n f$$

$$L\frac{dI}{dt}+(R_b+R_c)I+\frac{Q}{Cc}=V$$

where:

The proposed model simultaneously describes:

1. the degree of compensation;
2. drift–diffusion transport processes;
3. deep-level trap kinetics;
4. temperature-dependent effects;
5. contact resistance and capacitance;
6. the formation and evolution of self-oscillations.

Therefore, it can be considered a unified mathematical framework for describing self-oscillating current systems in compensated silicon. The model combines carrier transport, trapping–detrapping dynamics, electric-field redistribution, and external circuit effects within a single self-consistent formulation, providing a comprehensive explanation of the experimentally observed oscillatory phenomena.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The conditions for the occurrence of self-oscillations were investigated in silicon samples compensated with Mn, Se, and Zn impurities. The samples were fabricated from KDB-2 and KDB-10 silicon wafers. The impurities (Mn, Se, and Zn) were introduced by diffusion at temperatures of 1200–1250 °C. As a result, highly compensated materials with resistivities in the range of 10^3–10^5 Ω·cm were obtained.

For the formation of injection contacts, boron (B) and phosphorus (P) diffusion techniques were employed. The experimental results indicate that the onset voltage of self-oscillations (V_{onset}), the oscillation frequency (f), and the resistivity of the sample (ρ) strongly depend on the energy levels of the impurity atoms and on the degree of compensation.

The observed dependence confirms that deep-level impurity centers play a crucial role in the formation of self-oscillatory current regimes. Variations in impurity type and compensation level alter the carrier trapping and emission dynamics, which in turn affect the electrical instability conditions and the oscillation parameters of the injection structures.

Impurity	ρ (Ω·cm)	V_{onset} (V)	f (Hz)
Si<Mn>	5* 10^3	60-100	10^2 - 10^3
Si<Se>	1* 10^4	80-150	10^1 - 10^2
Si<Zn>	2* 10^3	40-80	10^3 - 10^4

According to the experimental results, the highest resistivity was observed in selenium-doped silicon samples, reaching approximately $\rho \approx 1 \times 10^4$ Ω·cm. Such a high resistivity can be attributed to the high degree of compensation and the corresponding reduction in the concentration of free charge carriers. As a consequence, a stronger electric field is required to initiate self-oscillations, and the onset voltage (V_{onset}) is found within the range of 80–150 V. At the same time, due to the increased carrier relaxation time, the oscillation frequency remains relatively low and is observed in the range of 10^1–10^2 Hz.

In manganese-doped silicon samples, the resistivity is approximately $\rho \approx 5 \times 10^3$ Ω·cm, which is lower than that of the selenium-doped samples. Accordingly, the onset voltage of self-oscillations decreases and falls within the range of 60–100 V. The oscillation frequency is found to be in the range of 10^2–10^3 Hz. This behavior is associated with the active participation of deep energy levels introduced by Mn atoms in the trapping and re-emission processes of charge carriers.

In zinc-doped silicon samples, the lowest resistivity value was recorded, approximately $\rho \approx 2 \times 10^3$ Ω·cm. The reduced resistivity facilitates a more rapid redistribution of the electric field within the sample. Consequently, self-oscillations arise at relatively low voltages, typically in the range of 40–80 V. These samples exhibit the highest oscillation frequencies, reaching the range of 10^3–10^4 Hz. This indicates that the charge-exchange processes associated with Zn-related centers occur at a significantly higher rate than those associated with Mn- and Se-related centers.

The obtained results indicate that the frequency of self-oscillations is inversely proportional to the resistivity of the material:

$$f \propto 1/\rho$$

This relationship is governed by the rate of electric-field redistribution within the sample and by the relaxation time of charge carriers. As the resistivity decreases, the relaxation time becomes shorter, leading to an increase in the oscillation frequency of the system.

In addition, a direct relationship exists between the onset voltage of self-oscillations and the resistivity:

$$V_{onset} \propto \rho$$

This dependence can be explained by the fact that a stronger electric field is required in high-resistivity samples to establish the negative differential resistance (NDR) regime necessary for the initiation of self-oscillations.

Therefore, the experimental results demonstrate that the main parameters of self-oscillations in compensated silicon are strongly dependent on the impurity type, the nature of the deep energy levels, and the degree of compensation. Zn-doped silicon samples are promising for the development of high-frequency self-oscillating generators, whereas Se-doped samples are more effective for generating low-frequency relaxation oscillations.

VI. CONCLUSION

In this work, the physical mechanisms of self-oscillating current systems observed in compensated silicon were investigated through both theoretical and experimental approaches, and a unified physical–mathematical model describing these phenomena was proposed. The model incorporates donor–acceptor compensation, drift–diffusion transport processes, generation–recombination phenomena, deep-level kinetics, impurity atom nanoclusters, temperature effects, and contact effects within a single self-consistent framework.

The results demonstrate that the occurrence of self-oscillations in compensated silicon is closely associated with the electron trapping and emission properties of impurity nanoclusters formed during the diffusion process. The interaction of the electric field, temperature, and local potential landscape leads to the spatiotemporal redistribution of charge carriers, resulting in periodic variations of the current. Based on the developed mathematical model, it was shown that the onset of self-oscillations is closely related to the formation of a negative differential resistance (NDR) region. Furthermore, the oscillation parameters were found to depend significantly on the impurity type, degree of compensation, electric-field strength, and temperature.

Experimental investigations revealed that silicon samples doped with Mn, Se, and Zn impurities exhibit different onset voltages and oscillation frequencies. Se-doped samples are characterized by high resistivity and low-frequency relaxation oscillations, whereas Zn-doped samples demonstrate high-frequency self-oscillations at relatively low applied voltages. Mn-doped samples exhibit intermediate characteristics between these two cases.

The analysis further showed that the self-oscillation frequency is inversely proportional to the resistivity, while the onset voltage varies directly with resistivity. These relationships are in good agreement with the predictions of the proposed model and confirm its physical validity.

The obtained results are of considerable scientific and practical importance for the development of next-generation self-oscillating generators, frequency converters, sensitive sensor elements, and nonlinear electronic devices based on compensated silicon. The proposed model also provides a foundation for future investigations of self-oscillation phenomena in compensated semiconductors and offers new opportunities for controlling their characteristics through material and device engineering.

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