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# LONG-TERM RELAXATION PROCESSES OF ELECTRICAL CONDUCTIVITY IN COMPENSATED Si<B,S> AND Si<B,Rh> MONOCRYSTALS

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In this paper, the processes of conductivity relaxation in Si<B,S> and Si<B,Rh> single crystals under different compensation conditions and concentrations are investigated. It is found that the relaxation process of photoconductivity in compensated Si<B,S> and Si<B,Rh> single crystals is described by a two-step exponential dependence with characteristic times of fast ($\tau_1$) and slow ($\tau_2$) relaxation, and these relaxation processes depend on the type of compensating impurity and its concentration. The relaxation parameters ($\tau_1$, $\tau_2$) were determined and it was found that the characteristic relaxation time of the photocurrent in the Si<B,Rh> sample is much shorter compared to the Si<B,S> sample. With increasing γ-irradiation dose, the second characteristic relaxation time ($\tau_2$) first sharply increases and then reaches the saturation state at a certain high dose, which is explained by the limited number of deep energy defects formed under irradiation. The dependence of the relaxation time ($\tau_2$) on the γ-radiation fluence increases with decreasing temperature (up to 77 K). The influence of fluctuations in the concentration of charge carriers on the relaxation process is investigated, and it is found that with a decrease in the resistivity of the starting material, i.e. at higher concentrations, the amplitude of fluctuations increases, which leads to an increase in the relaxation time.
**Keywords:** *Film; Si<B,S>; Si<B,Rh>; γ-radiation; Photoconductivity; Relaxation time; Temperature; Concentration*
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## INTRODUCTION

Modern electronics and solar energy together with photonics require an increasing demand for high-efficiency semiconductor materials. Compensated semiconductors represent an effective method for the development of these materials. The compensation method adds dopants with opposite charges to semiconductors, which allows scientists to control electrical properties and photoelectric characteristics and conductivity type and carrier concentration. Boron-doped silicon, which receives compensation through sulfur (S) or rhodium (Rh) atoms, emerges as the most critical silicon-based compensated material [1,2]. Compensated Si<B,S> and Si<B,Rh> monocrystals demonstrate high photosensitivity properties that make them suitable for solar energy systems and photodetectors and radiation-resistant electronic devices [3]. Such materials demonstrate changing electrical conductivities through time due to the occurrence of relaxation processes. The nature of relaxation processes needs thorough analysis because it enables enhancements in material properties including photosensitivity and electrical conductivity as well as radiation resistance [4]. The long-term relaxation behavior of electrical conductivity in Si<B,S> and Si<B,Rh> materials demands scientific investigation due to its practical value. The current research analyzes the electrical conductivity relaxation characteristics of Si<B,S> and Si<B,Rh> monocrystals under different compensation conditions and impurity concentration levels.

## RESEARCH METHODS

The researchers used boron-doped p-type silicon (Si) monocrystals because they selected them as starting materials. The starting Si<B,S> samples displayed specific resistivity values between 1 to 10 Ω·cm while Si<B,Rh> samples showed specific resistivity between 7 to 10 Ω·cm. The implement of thermodiffusion enabled compound creation through the specified temperature range from 1250 to 1290°C for a complete duration of 20 hours. The concentration development of compensating sulfur (S) atoms in Si<B,S> samples reached $N_S$ between $(0.2\text{-}2)\cdot 10^{16}$ cm$^{-3}$ and Si<B,Rh> samples contained rhodium (Rh) atoms at $N_{Rh} \approx 5\cdot 10^{15}$ cm$^{-3}$. The specific resistivity rose dramatically through compensation in both sample types which led to the creation of high-resistivity silicon monocrystals with $\rho = (8\text{-}10)\cdot 10^4$ Ω·cm.

## RESULTS AND DISCUSSION

### Relaxation Processes of Electrical Conductivity

It is well established that photoconductivity relaxation refers to the decay of photocurrent in semiconductor materials after the cessation of photoexcitation. This process is a key parameter characterizing the electro-optical properties of the material. For the Si<B,S> and Si<B,Rh> monocrystals under investigation, this relaxation process can be accurately described by a two-stage exponential law [5]:

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$$I_\Phi = A_1 e^{-t/\tau_1} + A_2 e^{-t/\tau_2} \quad (1)$$

In this context, $I_\Phi$ – denotes the time-dependent photocurrent, while $A_1$ and $A_2$ $_2$ represent the initial amplitudes of the photocurrent components. The parameters, $\tau_1$ and $\tau_2$ $_2$ are the characteristic time constants of the relaxation process [6]. According to the authors of [6], these parameters are strongly dependent on the type and concentration of the compensating impurity. Typically, the condition $A_1 \gg A_2$ and $\tau_1 \ll \tau_2$ is fulfilled, indicating the presence of two distinct mechanisms involved in the relaxation process—one fast and one slow. Table 1 presents the characteristic values of the relaxation parameters determined from experimental investigations conducted on Si<B,S> and Si<B,Rh> monocrystals. These values reflect the unique properties of the compensated materials. The data in the table provide a basis for evaluating the photosensitivity and response speed of the materials, and demonstrate the potential of creating highly photosensitive semiconductors through compensation techniques for practical applications [7].

**Table 1.** Photoconductivity Relaxation Parameters

| Sample type | Expression | $\tau_1$ | $\tau_2$ |
|---|---|---|---|
| Si<B,S> (1) | $I_\Phi = 4\cdot 10^{-2} e^{\frac{t}{9}} + 2{,}5\cdot 10^{-2} e^{\frac{t}{6184}}$ | 9 | 6184 |
| Si<B,S> (2) | $I_\Phi = 1\cdot 10^{-7} e^{\frac{t}{261}} + 2\cdot 10^{-8} e^{\frac{t}{4121}}$ | 261 | 4121 |
| Si<B,S> (3) | $I_\Phi = 1\cdot 10^{-3} e^{\frac{t}{160}} + 5\cdot 10^{-5} e^{\frac{t}{1060}}$ | 160 | 1060 |
| Si<B,Rh> | $I_\Phi = 2\cdot 10^{-5} e^{\frac{t}{0.72}} + 4{,}5\cdot 10^{-8} e^{\frac{t}{53}}$ | 0.72 | 53 |

The Si<B,Rh> sample exhibits a considerably reduced relaxation time than the Si<B,S> sample. The different materials exhibit different potential barrier heights because of this observation. The scientific importance of studying how external gamma radiation doses affect photoconductivity relaxation processes is widely acknowledged as a fundamental concept. Semiconductor materials undergo such radiation analysis to evaluate their resistance to radiation according to research in [8]. This research analyzed the effect of different γ-irradiation doses on the photocurrent relaxation behavior in Si<B,S> and Si<B,Rh> material samples. Figure 1 displays the second characteristic relaxation time ($\tau_2$) variations with increasing γ-irradiation dose according to graphical results.

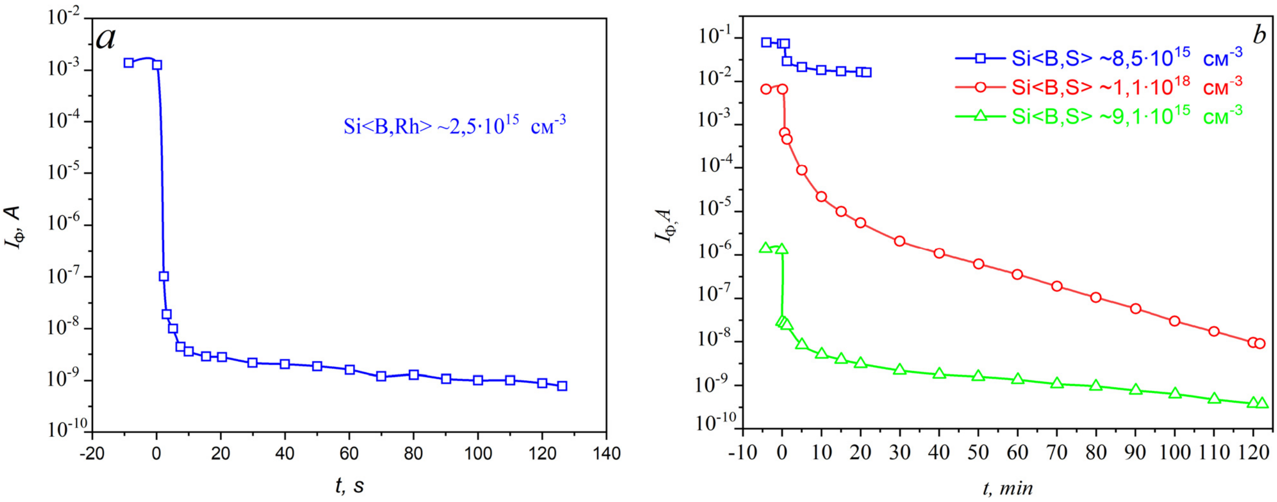


**Figure 1.** Dependence of photoconductivity relaxation kinetics on γ-radiation dose
*a*) Si<B,Rh> sample $N_{Rh}^{d}$~$2.5\cdot 10^{15}\ cm^{-3}$; b) Si<B,S> sample 1 – $8.5\cdot 10^{15}\ cm^{-3}$, 2 – ~$9.1\cdot 10^{15} cm^{-3}$, 3 – ~$1.1\cdot 10^{18}\ cm^{-3}$

Results analysis demonstrated that the second characteristic relaxation time ($\tau_2$) started with substantial growth until it stabilized at a saturation point under high dose exposure of γ-irradiation. The saturation amount depends on atom type Rh or S together with atom concentration. The two slow recombination pathways for photo-generated carriers in compensated Si<B,S> and Si<B,Rh> monocrystals emerge as the result of these experimental findings [9].

The slow decay of photocurrent follows the second characteristic relaxation time ($\tau_2$) primarily because deep energy centers exist within the semiconductor. Different types of deep-level energy traps known as defect centers are generated or their concentration grows within Si<B,S> and Si<B,Rh> materials when the γ-irradiation dosage increases [10]. The charge carriers become trapped by these defects, which decelerates their recombination rate until the relaxation time $\tau_2$ extends. When the dose of irradiation reaches, its critical level the creation and density of these defects will become saturated [11]. The total number of deep-level centers reaches its maximum limit at the same time as their carrier capture capability reaches saturation. After reaching this saturation point the additional dose becomes ineffective since it fails to modify the relaxation time value of $\tau_2$—and this stage is referred to as the saturation regime. The evolution of this process depends on both the type and amount of compensating impurity because each impurity atom affects the silicon crystal lattice structure and the carrier recombination patterns differently according to literature [12]. The research findings establish essential evaluation criteria for assessing radiation resistance in compensated Si<B,S> and Si<B,Rh> samples making them suitable materials for building radiation-resistant photosensitive semiconductors [13].

### Analysis of the Influence of Radiation and Temperature on the Relaxation Process

In order to gain a deeper understanding of the photoconductivity relaxation process in semiconductors, it is essential to consider the impact of external factors such as radiation fluence and temperature. As γ-irradiation dose increases, the number of defects in the semiconductor also rises, which in turn modifies the recombination processes of charge carriers [14]. Figure 2 presents the influence of γ-radiation doses on the photocurrent relaxation time in the Si<B,Rh> sample as a function of temperature.

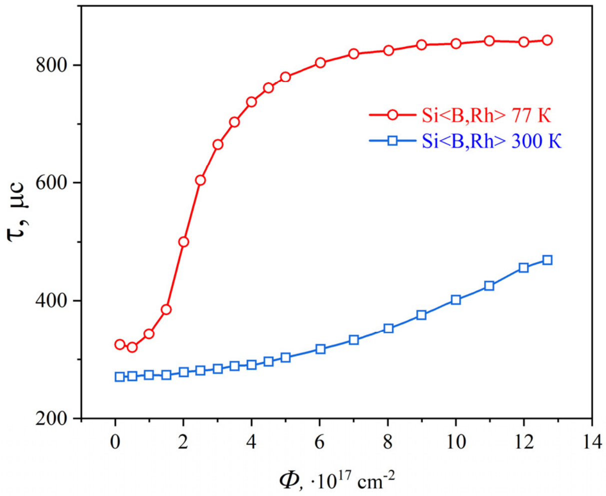


**Figure 2.** Dependence of Relaxation Time $\tau_2$ on γ-radiation and temperature in the Si<B,Rh> Sample: 1 – 77 K; 2 – 300 K

Results in Figure 2 show that the relaxation time changes at a faster rate when γ-radiation increases at 77 K low temperature conditions. When temperatures decrease the number of thermally activated charge carriers decreases so recombination happens mostly through deep-level defect centers produced by irradiation [15]. Each defect center plays a stronger role because of which the relaxation process experiences a more noticeable slowdown.

The number of thermally activated carriers rises at 300 K leading to weakened interactions between charge carriers and defects that causes the relaxation time to change more slowly [16]. The temperature increase reduces the fluence-dependence of relaxation times. The necessity of high fluence sensitivity in relaxation time comes forth as fundamental for creating radiation-tolerant photoelectronics designed to operate at cold temperatures.

### Effect of Concentration Fluctuations on the Relaxation Process

During the compensation of semiconductor materials, fluctuations in charge carrier concentration-i.e., variability in carrier density-can have a significant impact on electrical conductivity and photocurrent relaxation. These fluctuations lead to local distortions in the energy bands of compensated semiconductors, resulting in the formation of potential barriers [17]. Consequently, the mobility of charge carriers decreases, and their recombination process slows down, which leads to an increase in relaxation time.

Table 2 presents the amplitude of charge carrier concentration fluctuations and their relative variation with respect to the mean value for Si<B,S> materials at a compensation level of $K = 1$.

**Table 2.** Dependence of Concentration Fluctuations on Material Type in Si<B,S> Samples with a Compensation Level of K = 1

| # | $P^{max}, cm^{-3}$ | $P^{min}, cm^{-3}$ | $\bar{P}, cm^{-3}$ | $\frac{P^{max} - P^{min}}{\bar{P}} \cdot 100\%$ | $\bar{N}_S, cm^{-3}$ |
|---|---|---|---|---|---|
| 1 | $2.1 \cdot 10^{16}$ | $1.9 \cdot 10^{16}$ | $2 \cdot 10^{16}$ | 10 | $2 \cdot 10^{16}$ |
| 2 | $2.1 \cdot 10^{15}$ | $1.9 \cdot 10^{15}$ | $2 \cdot 10^{15}$ | 10 | $2 \cdot 10^{15}$ |

The data shows that higher carrier concentrations lead to larger absolute fluctuations of charge carrier concentrations that correspond to lower specific resistivity values of initial materials. The process produces enhanced potential barriers, which grow in both height and quantity. Lower specific resistivity values in the material result in increased recombination times for charge carriers according to the table data analysis. During the process, time the number of barriers and height, increase simultaneously. The reduction of specific resistivity extends charge carrier recombination time because photoconductivity relaxation duration stretches out.

The relaxation time length becomes extended when the initial material has lower specific resistivity levels as this produces higher charge carrier concentration fluctuations to enhance photosensitivity. This research discovery has immense potential to improve the creation of photodetectors while creating high-sensitivity sensor devices.

## CONCLUSIONS

Scientific and practical findings from the research evaluation enabled researchers to establish these main conclusions:

Compensated Si<B,S> and Si<B,Rh> monocrystals exhibit two-stage exponential relaxation which proceeds through fast ($\tau_1$) and slow ($\tau_2$) relaxation times during photoconductivity decay. The relaxation processes showed significant dependence on the type together with the concentration level of the compensating impurity used.

The experimental results revealed that the Si<B,Rh> sample had a substantially reduced characteristic relaxation time of its photocurrent compared to the Si<B,S> sample.

γ-radiation doses lead to an abrupt upswing of the second characteristic relaxation time ($\tau_2$) before it reaches an equilibrium state at a particular high dose level. The saturation occurs because radiation exposure creates only a limited number of deep-level energy defects.

When the γ-radiation flux was assessed at 77 K the dependency of relaxation time ($\tau_2$) became more significant. Low temperatures lead to mostly recombination through defect centers that form due to irradiation. Thus, a decrease in the specific resistivity of the initial material enhances the concentration fluctuations of charge carriers and creates the potential to improve the material's photosensitivity through the prolongation of the relaxation time.

This finding is particularly important for the development of photodetectors and highly sensitive sensor devices.

### Conflict of Interests

The authors declare that they have no conflict of interests

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## ДОВГОТРИВАЛІ ПРОЦЕСИ РЕЛАКСАЦІЇ ЕЛЕКТРОПРОВІДНОСТІ В КОМПЕНСОВАНИХ МОНОКРИСТАЛАХ Si<B,S> TA Si<B,Rh>

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У цій статті досліджуються процеси релаксації провідності в монокристалах Si<B,S> та Si<B,Rh> за різних умов компенсації та концентрацій. Встановлено, що процес релаксації фотопровідності в компенсованих монокристалах Si<B,S> та Si<B,Rh> описується двоступеневою експоненціальною залежністю з характерними часами швидкої ($\tau_1$) та повільної ($\tau_2$) релаксації, причому ці процеси релаксації залежать від типу компенсуючої домішки та її концентрації. Визначено параметри релаксації ($\tau_1$, $\tau_2$) та виявлено, що характерний час релаксації фотоструму у зразку Si<B,Rh> значно коротший порівняно зі зразком Si<B,S>. Зі збільшенням дози γ-опромінення другий характерний час релаксації ($\tau_2$) спочатку різко збільшується, а потім досягає стану насичення при певній високій дозі, що пояснюється обмеженою кількістю глибоких енергетичних дефектів, що утворюються під час опромінення. Залежність часу релаксації ($\tau_2$) від флюенсу γ-випромінювання зростає зі зниженням температури (до 77 K). Досліджено вплив флуктуацій концентрації носіїв заряду на процес релаксації та виявлено, що зі зменшенням питомого опору вихідного матеріалу, тобто при вищих концентраціях, амплітуда флуктуацій збільшується, що призводить до збільшення часу релаксації.

**Ключові слова:** *плівка; Si<B,S>; Si<B,Rh>; γ-випромінювання; фотопровідність; час релаксації; температура; концентрація*