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INVESTIGATIONS OF THE DEEP-LEVEL PARAMETERS IN SEMICONDUCTORS

We propose to use methods involving a deformation for the determination of deep-level parameters in semiconductors. The methods are based on the measurement of strain parameters of compensated and overcompensated semiconductors. The dynamic changes of the current flow in compensated and overcompensated samples of the p-type Si : Ni and n-type Si : Mn under a uniform pulse hydrostatic compression (UHC) are investigated. It is observed that, in the p-type Si : Ni samples the, ionization energy level of Ni increases at UHC. On the contrary, it decreases in samples of the n-type Si : Mn. The ionization energy and the baric coefficient of shift of Ni and Mn levels are bounded.

Keywords: deformation, impurities, strain resistance, hydrostatic pressure.

1. Introduction

In the pulse regime of the action of a uniform hydrostatic pressure (UHP) in semiconductors with deep levels of impurities, the resulting combined strain-thermo-effect causes an additional change of the conductivity in semiconductors with various degrees of filling of the deep levels [1]. Therefore, a deformation technique is proposed allowing the investigation of not only the baric changes in semiconductors, but also the determination of the ionization energy, concentration, and other deep-level parameters without using additional techniques such as the temperature dependence of the Hall effect, capacity spectroscopy, DLTS, *etc.* [2].

2. Samples and Methods of Measurements

The presented method is based on measuring the strain parameters of compensated and overcompensated semiconductors. During the investigation, we used samples of the p-type Si : Ni and the n-type Si : Mn silicon with the resistivity $\rho = 10^5\ \Omega\cdot$cm obtained on a monocrystal silicon base, using SDP-15 (silicon doped with phosphorus) and SDP-4 (silicon doped with boron) technologies, as described in [3].

The investigated silicon samples had the shape of a parallelepiped $2 \times 2 \times 4$ mm^3 in size. To measure the temperature of samples during the process, a copper/constantan thermocouple was tightly pressed to the sample surface. To prevent the thermal scattering and to increase the accuracy of the temperature measurements, the samples were wrapped up with a thermocouple in a thermal-insulation envelope formed of epoxy glue. The reference thermocouple was held at 0 °C. Control measurements of the electrical conductivity and temperature of the sample-thermocouple system under the application of pressure impulses showed that they are changed simultaneously over the interval $T = 243\div293$ K and $P = (0\div5) \times 10^8$ Pa. The required external pressures were produced via an UHP installation with a pneumatic amplifier [4], which created pressure pulses with slow rate $\partial P/\partial t = 10^8$ Pa/s in the temperature interval $T = 273\div293$ K.

3. Experimental Results

The kinetics $I = f(t)$ for a p-type Si : Ni sample over the range of impulse action (region 1) and under UHP (region 2) at the initial operating temperature $T_0 = 273$ K is shown in Fig. 1. Measurements showed that when the pressure increases in the interval $P = (0\div5) \times 10^8$ Pa, the temperature of samples abruptly increases to $T_{\max}$, a value ranging from 243 K to 293 K, by depending on the pressure and $\partial P/\partial t$. The current in samples increases from $I_0 = 3.7\times10^{-6}$ A to $I_{\max} = 6.8\times10^{-6}$ A according to the temperature of samples (Fig. 1, region 1). After the removal of the pressure, the temperature of a

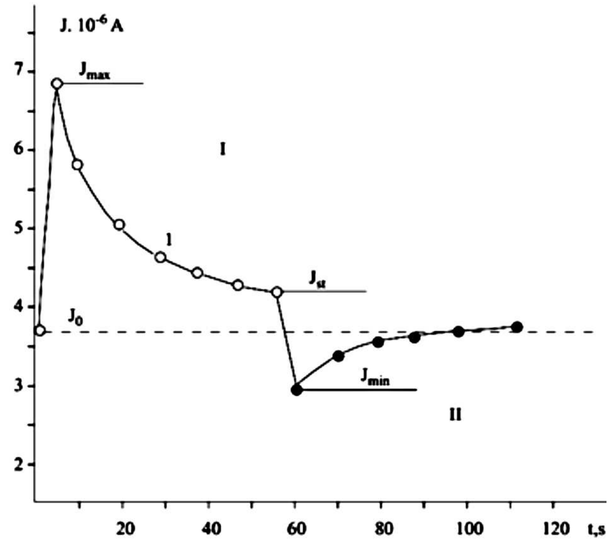
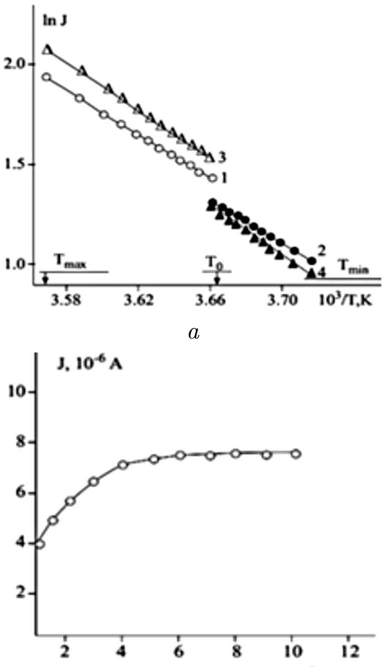


Fig. 1. Kinetics of a current flow in the p-type Si : Ni samples under the pulse action (*1*) and the removal of UHP with the rate $\frac{\partial P}{\partial t} = 10^8$ Pa/s at the initial operating temperature $T_0 = 273$ K



a

b

Fig. 2. Temperature dependence of a current in the p-type Si : Ni samples (*1, 2*) and the n-type Si : Mn (*3, 4*) under the UHP (*1, 3*) action and without a pressure (*2, 4*) at $T_0 = 273$ K *a*. Dependence of amplitude values on the current in the p-type Si : Ni samples on the rate of UHP pressure change with the amplitude $P = 5 \times 10^8$ Pa at $T_0 = 273$ K *b*

sample relaxed to its static value during 50÷60 s at $P = (0{\div}5) \times 10^8$ Pa.

Unlike the influence of UHP, when reducing the pulsed pressure, the temperatures and currents of samples firstly decrease to values $T_{\min}$ and $I_{\min}$, respectively, from which they relax to their initial values, i.e. to T_0 and I_0 (Fig. 1, region 2). The similar dependence of $I = f(t)$ under similar conditions and UHP was obtained for the n-type Si : Mn samples. Measurements of the Hall effect in the p-type Si : Ni and n-type Si : Mn samples under the UHP impulse action at temperatures $T_0, T_{\max}$ and $T_{\min}$, i.e. at the extreme point changes of $I_{\max}$ and $I_{\min}$, showed that a change of the current in the samples is essentially due to a change of the concentration of current carriers (≈96), since, under these experimental conditions, their mobility changes slightly (≈4).

4. Processing of Experimental Results

The dynamical changes of the conductivity in overcompensated samples of the p-type Si : Ni and n-type Si : Mn for impulse UHP can be presented in the form [6]:

$$I = Ue\mu n\,(P,T) \times S/L = \\ = Ue\mu n_0\,[\exp\,(-E_i - \alpha_i P)/kT] \times S/L, \qquad (1)$$

where U is the voltage applied to sample; S and L are the cross-section and length of a sample; e, μ, and n are the charge, mobility, and concentration, respectively, of current carriers, E_i and α_i are the energy of an impurity level and pressure of this level, respectively; P is the value of UHP; T is the temperature of a sample; and k is Boltzmann constant. By taking the logarithm and differentiating with respect to the temperature, expression (1) can be rewritten as

$$\partial\,(\ln J)/\partial E = \partial\,(\ln Ue\mu n_0 S/L)/\partial E - \\ - k^{-1}\,(E_i - \alpha_i P)\,(\partial\,(1/T)/\partial T). \qquad (2)$$

Taking into account that $\partial\,(\ln Ue\mu n_0 S/L)/\partial T \approx 0$, we get the ionization energy of impurity levels E_i:

$$E_i = -k\,[\partial\,(\ln I)/(\partial T)\,(\partial\,(1/T)\,\partial T) + \alpha_i P]. \qquad (3)$$

From this, one can see that E depends on the rates of changes of I and T. The temperature dependences of the current in the samples of the p-type Si : Ni (curve *1* and *2*) and the n-type Si : Mn (curve *3* and *4*) are given in Fig. 2, *a*. They correspond to the experimental results of relaxed regions 1 and 2 in Fig. 1. Ionization energy levels for Ni and Mn as functions of their baric shift coefficient are defined according to expression (3). The experimental results are given in Fig. 2. Energy levels $E_{N_i} = 0.42$ eV and $E_{M_n} = 0.52$ eV were calculated, by using $\alpha_{\mathrm{Ni}} = 1.2 \times 10^{-11}$ eV/Pa and $\alpha_{\mathrm{Mn}} = 1.8 \times 10^{-11}$ eV/Pa, respectively. These results confirm those in [3, 4].

The maximum current as a function of the pressure change rate at UHP $I_{\max} = f\,(\partial P/\partial t)$ with amplitude $P = 5 \times 10^8$ Pa in the p-type Si : Ni samples with the initial operating temperature $T = 293$ K is plotted in Fig. 2, *b*. One can see that the maximum current amplitude monotonically increases with the rate and, at certain values, the change of the current depends on the rate $(\partial P/\partial t) = 10^8$ Pa/s, resulting in the plateau observed in $I(P)$.

Thr analysis of experimental data shows that the plateau appears to be independent for $I_{\max} = f\,(\partial P/\partial t)$ and is linked with the full atom ionization in the Ni impurity levels in Si.

In the studied system, i.e. the p-type Si : Ni, the electric neutrality equation of the current of carriers in the region full of "feeble" Ni levels may be written as [5]:

$$p = N_{\mathrm{A}} - N_{\mathrm{D}},$$

where $N_{\mathrm{A}} = N_{\mathrm{D}} + p$, and N_{D} is the concentration of minor donors, and N_{A} is the concentration of compensated acceptors of impurities. In the investigated samples of the p-type Si : Ni, the full concentration of electrically active atoms proves to be equal to 3.47×10^{14} cm^{-3} and is in good agreement with the data in [6].

5. Conclusion

The studied method of pulse-action UHP may be used successfully to determine some baric deep level parameters via the baric measurements in semiconductors.

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ДОСЛІДЖЕННЯ ПАРАМЕТРІВ ГЛИБОКОГО РІВНЯ В НАПІВПРОВІДНИКАХ

Резюме

У роботі пропонуються методи деформації для дослідження параметрів глибокого рівня в напівпровідниках. Він базується на вимірах параметрів деформації компенсованих і надкомпенсованих напівпровідників. Досліджено динамічні зміни струму в компенсованих та надкомпенсованих зразках p-типу Si : Ni та n-типу Si : Mn при однорідному імпульсному гідростатичному стискуванні (ОГС). Встановлено, що в p-типу Si : Ni зразках енергія іонізації Ni при ОГС збільшується. Навпаки, вона зменшується в зразках n-типу Si : Mn. Енергія іонізації та баричний коефіцієнт зсуву рівнів Ni і Mn були обмеженими.