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REGULAR ARTICLE

Effect of Uniaxial Compression on Excitation Conditions and Parameters of Low-Frequency Auto-Oscillations of Current in Compensated Silicon

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In compensated silicon doped with impurity atoms creating deep energy levels in the band gap of the material, a number of interesting physical phenomena have been found that are not only of scientific interest but also have great practical significance. One of them is low-frequency auto-oscillations of current, which are excited in certain conditions In this paper we consider the influence of the uniaxial elastic com-pression on the parameters of current auto-oscillations. The research was carried out in silicon samples doped with impurity manganese atoms with crystallographic directions <111>, <110> and <100>. It has been found that the character of change of excitation conditions and parameters of auto-oscillations depend on the crystalline directions. Unusual change in the threshold electric field strength (E_{th}) and parameters (amplitude, frequency) of current auto-oscillations in compensated silicon samples with crystallographic direction <100>. The physical mechanism of parameter changes and the conditions of excitation of current auto-oscillations are explained with the change in the population of the deep energy level by doubly ionized manganese atoms. From the analysis of the obtained results and according to theoretical concepts, the physical mechanism of the change of parameters and conditions of excitation of current auto-oscillations under the influence of uniaxial elastic compression is explained.

Keywords: Silicon, Amplitude, Frequency, Manganese, Crystallographic direction, Ionization energy, Auto-oscillations.

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1. INTRODUCTION

In recent years, with the growth of requirements for information processing and their transmission to a distance, scientists and specialists have begun to study various current auto-oscillations found in semiconductor materials and structures. These studies show that in certain thermodynamic conditions in compensated silicon doped with impurity atoms, creating deep energy levels in the band gap of the material are observed a number of interesting physical phenomena, one of these phenomena are low-frequency current auto-oscillations. From the literature analysis, it was found that the study of current auto-oscillations found in compensated silicon doped with impurity manganese atoms is not only of scientific interest but is of great practical im-portance [1-4]. The study has established that under certain conditions in compensated silicon excite low-frequency auto-oscillations of current (temperature-electrical instability - TEI) found in compensated silicon doped with impurity manganese atoms, which are very sensitive to changes in the conditions of external influence, especially uniaxial elastic compression [5-8].

The results of studies on the influence of external influence of various physical quantities on the conditions of excitation and parameters of current auto-oscillations allow, on the one hand, to evaluate the performance of solid-state oscillators based on compensated silicon doped with impurity manganese atoms, as well as the possibility of creating sensitive sensors with amplitude-frequency output. The study of the effect of uniaxial elastic compression on the parameters of cur-rent auto-oscillations allows us to find out the physical mechanism of excitation of current auto-oscillations and to determine the energy level of the impurity manganese atom in the silicon band gap, responsible for the excitation of auto-oscillations. The effect of uniaxial compression on the excitation conditions and parameters of low-frequency current auto-oscillations generated in single-crystal silicon compensated by impurity manganese atoms was studied under the simultaneous influence of an applied electric field and monochromatic radiation in the region of intrinsic absorption [9-11].

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2. METHODOLOGY

To obtain compensated silicon with maximum electroactive concentration of doping manganese atoms, single-crystal silicon with crystal orientation axis <111>, <110> and <100> of KDB-1; 10; 100 grades was used as initial samples, where boron concentration was NB = $2 \cdot 10^{16}$; $2 \cdot 10^{15}$; $2 \cdot 10^{14}$ cm^{-3}, respectively. The compensated silicon doped with impurity manganese atoms was obtained by the diffusion method from the gas phase. Computer calculation of the dependence of the diffusion coefficient of impurity manganese atoms on temperature allowed us to clearly determine the technological modes of diffusion, which made it possible to obtain samples of compensated silicon with different resistivities $\rho = 10^2 \div 10^5$ Ohm·cm and different types of conductivity (Table 1) [12, 13].

Table 1 shows that depending on the initial concentration of impurity boron atoms, at the same temperature and diffusion time of manganese atoms, it is possible to obtain materials with different resistivities and conductivity type.

Table 1 – Electrophysical parameters of compensated silicon at different diffusion temperatures and at different initial boron concentrations

Diffusion temperature, °C	KDB-1 NB = $2 \cdot 10^{16}$ sm^{-3}	KDB-10 NB = $2 \cdot 10^{16}$ sm^{-3}	KDB-100 NB = $2 \cdot 10^{16}$ sm^{-3}
1050	65 Ohm·sm, *p*-type	$2 \cdot 10^5$ Ohm·sm, *p*-type	$1.6 \cdot 10^3$ Ohm·sm, *n*-type
1100	80 Ohm·sm, *p*-type	$9.2 \cdot 10^3$ Ohm·sm, *n*-type	$4 \cdot 10^2$ Ohm·sm, *n*-type
1150	$1,2 \cdot 10^3$ Ohm·sm, *p*-type	$1.4 \cdot 10^2$ Ohm·sm, *n*-type	60 Ohm·sm, *n*-type
1200	$3,4 \cdot 10^3$ Ohm·sm, *p*-type	$8.5 \cdot 10^3$ Ohm·sm, *n*-type	$5.8 \cdot 10^3$ Ohm·sm, *n*-type

The influence of uniaxial elastic compression on the conditions of excitation and parameters of current auto-oscillations was carried out in a specially designed cryostat allowing to create the value of uniaxial compression up to $6 \cdot 10^8$ Pa in a wide range of temperatures $T = 80 - 400$ K and illumination of both integral light $I = 10^{-3} - 10^{2}$ lux and monochromatic radiation $\lambda = 1 - 3.5$ μm [14].

The effects of the magnitude of uniaxial elastic compression on the excitation conditions and parameters of current auto-oscillations depending on the three directions of the crystallographic orientation axis of compensated silicon, such as <111>, <110> and <100>. The study of the effect of uniaxial elastic compression of compensated silicon samples doped with impurity manganese atoms along the <111> crystalline direction shows that with the increase of the compression (*P*), the threshold value of the field E_{th} at which the current auto-oscillations are excited increased linearly with the coefficient $\alpha_1 = 2.3 \cdot 10^{-7}$ V/(sm·Pa), and for the <110> direction the coefficient was equal to $\alpha_2 = 10^{-7}$ V/(sm·Pa) (Fig. 1).

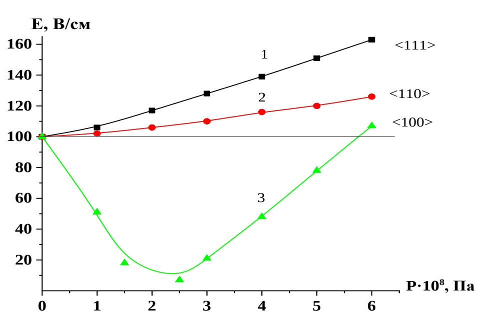


Fig. 1 – Variation of threshold electric field strength in silicon doped with impurity manganese atoms with different crystallographic directions as a function of uniaxial pressure, at $T = 80$ K, $I_f = 30$ lux

Studies have shown that the amplitude of the current auto-oscillation with increasing magnitude of uniaxial elastic compression also linearly increased with the coefficient $\alpha_1 = 6 \cdot 10^{-11}$ V/(sm·Pa) for silicon samples with crystallographic direction <111> and $\alpha_2 = 3 \cdot 10^{-11}$ V/(cm·Pa) for silicon samples with crystallographic direction <110>, and the frequency of the cur-rent auto-oscillation on the contrary monotonically decreased in these two directions of the crystal orientation axis (Fig. 2). At some critical value of uniaxial compression P_c, the auto-oscillations of the circuit collapsed, i.e., tensor damping of the current auto-oscillations was observed. It was found that the greater the value of the applied electric field strength (*E*), the greater the shift of the critical value of P_c at which the low-frequency auto-oscillations of the current break-down occurs.

From the analysis of the obtained results of the study it was found that the breakdown of the current auto-oscillations is associated with a linear growth of the threshold field (E_{th}) under the influence of uniaxial elastic compression. It was found that the relative change in the parameters of the current auto-oscillations was greater under compression of compen-sated silicon samples with crystalline direction <111>.

An unusual character of the change in the excitation conditions and parameters of current auto-oscillations is observed in the compression of compensated silicon doped with impurity manganese atoms with the crystallographic direction along the <100> axis.

Fig. 1 (3 curve) shows the variation of the threshold field E_{th} from the uniaxial compression along the crystallographic direction <100>.

As can be seen from Fig. 1, with increasing magnitude of uniaxial elastic compression, the value of E_{th} in contrast to the crystallographic directions <111> and <110> first decreases and reaches its minimum at the pressure value $P = 2.5 \cdot 10^8$ Pa. The studies have shown that the position of the minimum shifts towards higher pressure values with increasing intensity of integral illumination. At further growth of the value of uniaxial elastic compression the value of E_{th}^P begins to grow and at the value of compression $P = 5.4 \cdot 10^8$ Pa the threshold field strength becomes equal to the value without uniaxial elastic compression, and further exceeds it.

Thus, the change in the pore electric field strength E_{th}^P at which the current auto-oscillations are excited depending on the value of uniaxial elastic compression appears the area where $E_{th}^P<E_{th}^0$ shows that the threshold electric field at which the current auto-oscillations are excited significantly decreases under the influence of compression. The results of these studies show that in silicon samples doped with impurity manganese atoms with crystallographic directions <111> and <110> at the value of electric field strength (E) less than E_{th}^0 in the circuit auto-oscillations are not observed. In contrast to these samples of compensated silicon with crystallographic direction <100> at certain values less than Eth0 are excited auto-oscillations temperature-electrical instability (TEI) current stimulated by uniaxial elastic compression.

The pressure interval P at which auto-oscillations of the current stimulated by compression are observed decreases with decreasing value of the resistivity of the material and with increasing intensity of the integral illumination I. At $E_{th} < E_{th}^{P\max}$ the auto-oscillations in the circuit are disrupted regardless of the crystal direction of silicon samples doped with impurity manganese atoms. It is found that the relative change of E_{th}^P decreases with increasing intensity of integral illumination (I). It should be noted that the rate of change in the threshold electric field strength E_{th}^P at which excite current auto-oscillations depending on the pressure P in the samples of compensated silicon with the crystallographic direction <100> both in the region of decrease and in the region of increase varies with the baric coefficient of the order $\alpha \approx (7 \cdot 8) \cdot 10^{-7}$ V/(sm·Pa), which is 4-8 times greater than silicon samples in the other two crystallographic directions.

Simultaneously with the change of the threshold field under the influence of uniaxial compression, noticeable changes in the parameters of the current auto-oscillations in compensated silicon samples with the crystallographic direction <100> are observed. From the results of the study, it was found that regardless of the magnitude of the applied electric field strength, the amplitude of the current auto-oscillations up to the value of uniaxial elastic compression $P = 2.5 \cdot 10^8$ Pa decreases (Fig. 2 a, 3 curve), and the frequency increases (Fig. 2 b, 3 curve); at the value of $P > 2.5 \cdot 10^8$ Pa, on the contrary, the amplitude increases and the frequency decreases.

The analysis of the obtained research results showed that the most significant changes in the parameters of current auto-oscillations are observed at the values of E_{th} close to E_{th}^P. As can be seen from Fig. 2, the maximum changes in the parameters of the current auto-oscillations are observed at the value of uniaxial elastic compression $P = 2.5 \cdot 10^8$ Pa, with the amplitude changing by 5.5 times and the frequency by 50 times. Thus, at uniaxial elastic compression in the samples of compensated silicon with crystallographic direction <100> the character of change of parameters of current auto-oscillations in the investigated interval of uniaxial elastic compression differs significantly from the samples of silicon doped with impurity atoms with other crystallographic directions. It was found that the change in the parameters of current auto-oscillations under uniaxial elastic compression significantly exceeds the change in the fundamental electro-physical parameters of compensated silicon doped with impurity manganese atoms (resistivity, mobility of charge carriers, etc.).

3. RESULTS AND DISCUSSION

Analysis of the experimental data showed that the concentration of impurity europium atoms near the surface is 4.6 % atomic percent, which is sufficient to observe the interaction of the magnetic moments of impurity europium atoms [8].

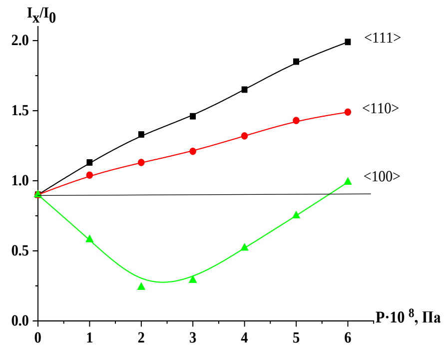
The data obtained using MFM for the initial and control annealed samples at the silicon diffusion temperature showed the absence of magnetic interaction forces.

Measurements on doped samples of diffusion silicon doped with impurity atoms of europium showed that in the absence of an external magnetic field, the magnetic forces in the samples are very small, but when an external magnetic field is applied, non-uniform magnetic forces begin to appear on the surface of the silicon samples and the range of these forces increases greatly with the magnetic field. Thus, the magnetic ordering of impurity atoms of europium with the transition of the ferromagnetic property of silicon is observed as "caused" by the magnetic field. It should be noted that in the obtained pictures, magnetic forces not only appear but also have a regular spatial order (Fig. 4 d, e).

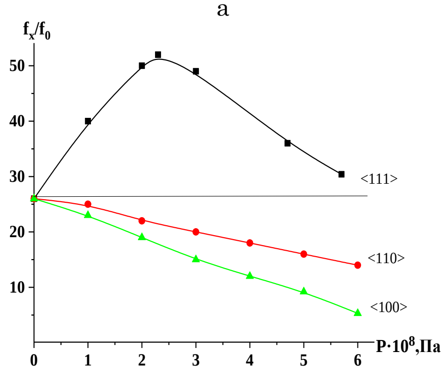
The mechanism of the change in the dependence of the parameters of current auto-oscillations on the magnitude of uniaxial elastic compression in different crystallographic axis orientations in samples of compensated silicon Si<B, Mn> can be explained from the following representations.

The presence of residual conductivity and temperature dependence of photocurrent in samples of compensated silicon doped with impurity manganese atoms gives grounds that the material is inhomogeneous in which drift (E_{dr}) and recombination (E_{rec}) barriers for holes are formed (Fig. 3) [15-17]. When the samples are illuminated, electrons move to the conduction zone, from there they are captured at deep energy levels, which are created by twice positively ionized manganese atoms E_{Mn}, and holes accumulate in the valence zone humps based on the difference in the capture cross section of the manganese $S_n >> S_p$ energy level.

When the concentration of holes at the level of flow is sufficient for Joule heating of the crystal there is a thermal generation of electrons from the energy level of manganese to the conduction zone in which there is a sharp increase in current, and then its decline due to recombination with holes in the valence zone. As a result of the value of photocurrent decreases the sample begins to cool down, when its temperature decreases, the original state is restored, i.e. the photosensitivity of the samples is restored and the process is periodically repeated.



a



b

Fig. 2 – Dependences of the amplitude (a) and frequency (b) of current auto-oscillations on the value of uniaxial elastic compression P for silicon samples doped with impurity manganese atoms with different crystallographic directions <111>, <110> and <100> at $E = 250$ V/cm, $I_0 = 9$ mA, $f_0 = 0.2$ Hz

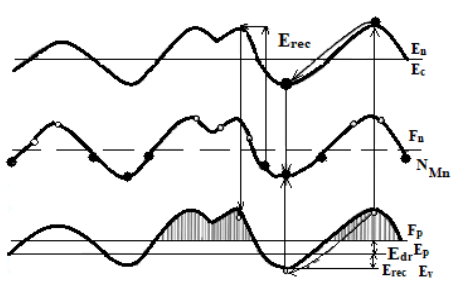


Fig. 3 – Zone diagram of compensated silicon doped with impurity manganese atoms based on the model of inhomogeneous semiconductor

From the analysis of the results of the study it is established that the values of amplitude, frequency and threshold field Eth of current auto oscillations in compensated silicon depend on the concentration of holes in the valence zone and the concentration of electrons at the energy level of twice ionized manganese atoms $E_{\rm Mn}$. The increase in the hole concentration (by decreasing the resistivity) leads to a decrease in the value of the threshold electric field strength (E_{th}), which leads to a change in the values of the amplitude and frequency of the current auto-oscillations. This assumption is con-firmed by the decrease of the current auto-oscillations Eth with the increase of the intensity of the integral illumination.

The results of studies have shown that for excitation of current auto oscillations in compensated silicon doped with impurity manganese atoms the main cur-rent carriers are holes. The obtained experimental data under the influence of uniaxial elastic compression on the parameters of auto-oscillations can be explained with a change in the mobility and concentration of holes. As it is known the change of mobility under uniaxial elastic compression with different crystallo-graphic directions in semiconductors is approximately the same. The concentration of holes at the level of percolation can increase due to a decrease in the drift barrier E_{dr} under the influence of uniaxial elastic com-pression, which should not depend on the crystallo-graphic direction because of the potential inhomogeneity barrier in samples of compensated silicon [18-20]. Therefore, it is impossible to explain by these two mechanisms such a sharp difference in the changes in the parameters of the current auto-oscillations under the influence of uniaxial elastic compression in compensated silicon samples with different crystallographic directions.

There remains one more mechanism leading to changes in the hole concentration in the valence zone under the influence of uniaxial elastic compression, which is associated with changes in the ionization energy of the deep energy level of manganese ($E_{\rm Mn}$) due to which the electron population at this level changes. According to the nature of dependences of the excitation threshold, amplitude and frequency of auto-oscillations depending on the magnitude of uniaxial elastic compression, it can be assumed that during compression in silicon samples with crystalline directions <111> and <110> the population of the manganese level $E_{\rm Mn}$ decreases due to the approach to it of the Fermi quasi-level. During compression in the <100> crystalline direction, the Fermi quasi-level first moves away from the deep level, which leads to an increase in its population, and then approaches it and leads to a decrease in the electron concentration population.

This decrease in the population of the deep level of impurity manganese atoms agrees well with the decrease in the population ionization energy during uniaxial elastic compression in the crystallographic direction <111>, since in this case all six valleys of the silicon conduction band fall down with the baric coefficient $\alpha_{111} = -2 \cdot 10^{-11}$ eV/Pa, and the deep manganese level with ionization energy $E_c - 0.5$ eV rises towards the conduction band with the coefficient $\gamma_{111} = 1.3 \cdot 10^{-10}$ eV/Pa. At compression in the <110> direction, all valleys rise upward with the baric coefficient $\alpha_{110} = 0.45 \cdot 10^{-11}$ eV/Pa, which is much smaller than in the first case, leading to a weak decrease in the ionization energy of the manganese level $E_c - 0.5$ eV and in the degree of its filling.

At compression of compensated silicon samples with a crystalline direction <100> two valleys of the conduction zone fall downward with a baric coefficient $\alpha_{100} = -4.72 \cdot 10^{-11}$ eV/Pa, while four valleys rise upward with a baric coefficient $\alpha_{100} = 3.57 \cdot 10^{-11}$ eV/Pa. The deep levels of impurity manganese atoms with ionization energy $E_c - 0.5$ eV rise toward the conduction zone with the coefficient $\gamma_{100} = -2.36 \cdot 10^{-10}$ eV/Pa. At small pressure values, the Fermi quasi-level rises with increasing uniaxial elastic compression (i.e., it approaches the bottom of the conduction zone) and moves away from the deep energy level of manganese $E_c - 0.5$ eV, which increases its population of electrons.

At large values of uniaxial elastic compression, electrons in the conduction zone completely move from the rising four valleys to the lowering two valleys at that the Fermi quasi-level together with the lowering valleys goes down. In this case, the Fermi quasi-level begins to approach the energy level of manganese with ionization energy $E_c - 0.5$ eV and its population decreases, which leads to an increase in the value of the pore electric field strength Eth. With the increase in the intensity of integral illumination I increases the concentration of electrons in the valleys, which leads to a shift of the Fermi quasi-level towards the deep level of impurity manganese atoms with ionization energy $E_c -$ 0.5 eV. In relatively large values of uniaxial elastic compression, the shift of the E_{th}^P minimum with increasing intensity of integral illumination I toward larger values of uniaxial elastic compression is explained by this physical mechanism.

4. CONCLUSION

A relatively large change in the parameters of low-frequency auto-oscillation of the current under the influence of uniaxial elastic compression in samples of compensated silicon doped with impurity manganese atoms with crystallographic direction <100> in comparison with the other crystallographic directions can be explained with a large rate of downward sinking of all six valleys of the conduction zone and upward displacement of the deep energy level of manganese with ionization energy $E_c - 0.5$ eV.

Analysis of the research results showed that, on the one hand, the parameters of the low-frequency current auto-oscillation are more sensitive to the effect of uniaxial elastic compression than the fundamental parameters of the original silicon, which makes it possible to create more sensitive strain gauges based on current auto-oscillations with amplitude-frequency output. On the other hand, with the help of these studies it is possible to describe more accurately the behavior of the Fermi quasi-level as a function of the crystallographic direction of silicon from the magnitude of uniaxial elastic compression. In addition, from the results of these studies we can determine the degree of filling of the deep energy level of impurity manganese atoms with ionization energy $E_c - 0.5$ eV. Determination of the degree of filling of the deep level is one of the main fundamental parameters of compensated semiconductors.

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Вплив одноосного стиснення на умови збудження та параметри низькочастотних автоколивань струму в компенсованому кремнії

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У компенсованому кремнії, легованому домішками, які створюють глибокі енергетичні рівні в забороненій зоні, виявлено низку цікавих фізичних явищ, що мають як наукове, так і практичне значення. Одним із таких явищ є низькочастотні автоколивання струму, які збуджуються за певних умов. У даній роботі розглядається вплив одноосного пружного стискання на параметри автоколивань струму. Дослідження проводились на зразках кремнію, легованих домішками марганцю, з орієнтацією по кристалографічних напрямках <111>, <110> та <100>. Встановлено, що характер зміни умов збудження та параметрів автоколивань (амплітуди, частоти) залежить від кристалографічного напряму. Особливу увагу привертає аномальна поведінка порогового електричного поля (E_{th}) і параметрів автоколивань у зразках з напрямком <100>. Фізичний механізм зміни параметрів та умов збудження автоколивань пояснюється зміною населеності глибокого енергетичного рівня двічі іонізованими атомами марганцю. Аналіз отриманих результатів, у поєднанні з теоретичними уявленнями, дозволяє пояснити вплив одноосного стискання на поведінку автоколивань струму в таких структурах.

Ключові слова: Кремній, Амплітуда, Частота, Марганець, Кристалографічний напрям, Енергія іонізації, Автоколивання.