ELECTRON MOBILITY IN $Ge_{1-x}Si_x$ ($0 \le x \le 0.13$) CRYSTALS COMPLEX DOPED BY <Ga,Sb,Ni> IMPURITIES

E.M. ISLAMZADE[1], Z.A. AGAMALIYEV[2], G.H. AJDAROV[1]

[1] *Institute of Physics of Azerbaijan NAS, AZ 1143, H.Javid ave.,131, Baku, Azerbaijan*
E-mail: zangi@physics.ab.az

[2]*Baku State University, AZ 1148, Z.Khalilov str., 23, Baku, Azerbaijan*
E-mail: zohrab@physics.ab.az

The temperature dependences of electron ohmic mobility in complex doped crystals $Ge_{1-x}Si_x$ <Ga, Sb, Ni> ($0 \le x \le 0.13$) in interval 77 – 300K are defined on the base of Hall coefficient and electric conduction measurements. The concentration order of shallow impurities in matrix is ~10^{16}cm^{-3}. It is seen that experimental data by free electron mobility in crystals after sample thermal treatment at 1000 – 1050K well coincide with calculative data taking under consideration the electron scattering on phonons, melt disorders, fully ionized impurities Ga, Sb, Ni and additional thermoinduced acceptor complexes.

Keywords: Ge, Ge-Si, complex doped, mobility, electroactive complexes.
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INTRODUCTION

The mobility of free charge carriers in semiconductors is the one of fundamental parameters characterizing the material. The value of mobility of electrons and holes in matrix is defined by concrete material structure band and interaction character of free charge carriers with lattice atom heat oscillations and series of crystal structure defects. The investigations of mobilities of (μ_e) electrons and (μ_h) holes in crystal solid solutions Ge-Si are carried out by many authors [1-5]. The change regularities μ_e and μ_h in dependence on temperature at phonon and melt scattering of free charge carriers in these crystals in wide temperature interval [4] are defined. The experiments are carried out mainly with samples doped by small impurity centers with concentration of 10^{14} – 10^{15} cm^{-3}order. In works [6,7] it is shown that experimental data on mobility of free charge carriers in complex doped crystals $Ge_{1-x}Si_x$ ($0<x<0.13$) with presence of cuprum multiacceptor impurity and small impurity centers with their general concentration by 10^{16} – 10^{17} cm^{-3} order well coincide with calculated data taking into consideration threefold acceptor behavior in matrix. Note that Ge-Si solid solutions with Si content up to 13% in reference are called germanium-like ones. This is connected with the fact that the conduction-band bottom in these crystal compositions forms by valleys in crystal-graphical directions /111/ as in germanium.

In recent work [8] the investigation results of main impurity state spectrum in complex doped crystals with presence of rapid diffusing doubly charged acceptor impurity Ni and shallow impurities Ga and Sb with concentration of 10^{16} cm^{-3} order. It is shown that thermal treatment of such samples at different T in 650-800^0 C interval leads to appearance of additional acceptor complexes (AC) including the atoms of Ni and Ga impurities. The activation energy of these complexes depends on $Ge_{1-x}Si_x$ crystal composition and is described by the expression $E_{AC}^x = E_v + (75 + 420x)meV$.

EXPERIMENT AND DISCUSSION

The results of experimental data analysis of electron mobility temperature dependences in Ge<Ga,Sb,Ni> complex doped crystals and germanium-like compositions of Ge-Si<Ga,Sb,Ni> solid solutions taking into consideration of twofold acceptor action of nickel impurity and appearance of additional acceptor complexes in matrix are given in the present work.

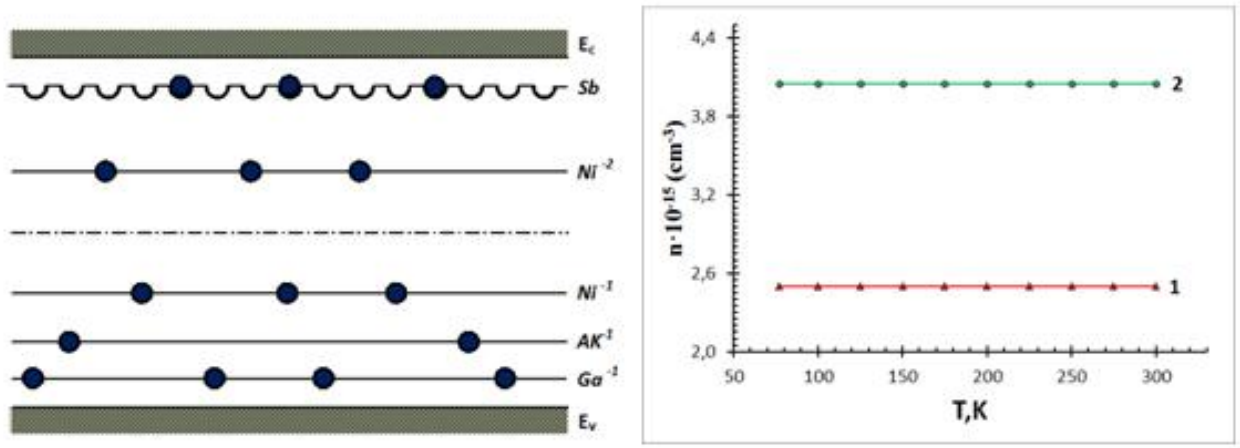
The purpose of the work is definition of experimental temperature dependences of electron mobility in complex doped $Ge_{1-x}Si_x$ ($0 \le x \le 0.13$) crystals by <Ga,Sb,Ni> impurities and establishment of quantitative interpretation possibility of obtained results within the framework of existing theories and conceptions taking into consideration the additional acceptor complexes and electron scattering on twofold ionized nickel impurities.

Ge crystals and germanium-like solid solutions Ge-Si with Si content up to 13 at% doped simultaneously by Ga and Sb are grown by modernized Bridgman method [8]. The concentration of both impurities in crystals is of 10^{16}cm^{-3} order. The doping of samples by nickel is carried by diffusion method at temperature corresponding to impurity maximum solubility in Ge-Si (875 -900^{0}C) crystals. The measurement of temperature dependences of Hall coefficient and sample electric conduction in 77-300K interval is carried before and after their doping by Ni and following thermal treatments at 750-800^{0}C.

At each temperature the samples are kept during a time which causes the presence of equilibrium state (3-4 hours [8]). The quenching is carried out by sample "disposal" in ethyl alcohol at dry ice temperature. The free electron concentration and their ohmic mobility in samples are defined using the data by electron Hall coefficient in Ge and corresponding compositions Ge-Si [4].

Sb, Al and Ni levels reveal in dependence on initial concentration of Ga and Sb impurities in samples after their doping by Ni at 875-900^{0}C. Here we consider only that samples, which before and after Ni doping and following thermal treatments at 750-800^{0}C, have electron conduction caused by excess concentration of Sb impurity under total concentration of all acceptor levels.

131 H.Javid ave, AZ-1143, Baku
ANAS, G.M.Abdullayev Institute of Physics
E-mail: jophphysics@gmail.com



A **B**

Fig.1. ***A*** is electron distribution scheme at *T*=0 on impurity energy levels in Ge and Ge-Si crystals complex doped by impurities Ga, Sb, Ni and thermoinduced AC with indication of center charge states;
B is temperature dependences of free electron concentrations in Ge<Ga,Sb,Ni,AK> (1) and $Ge_{0.9}Si_{0.1}$<Ga,Sb,Ni, AK> (2) crystals.

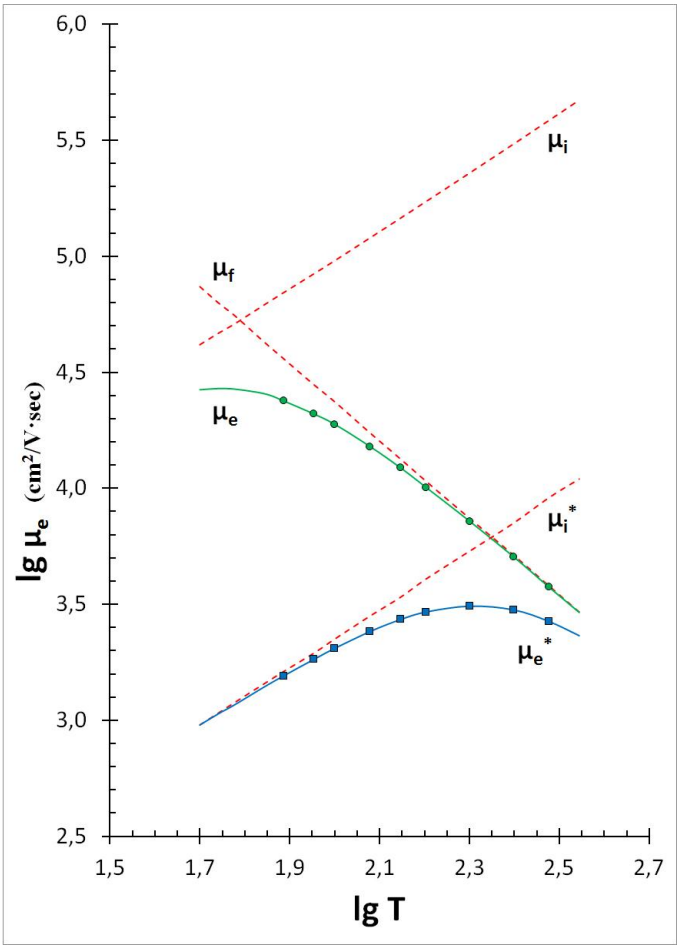


Fig.2. Temperature dependences of electron mobility in Ge<Sb> crystals with N_{Sb}=2.5·10^{15} cm^{-3} (μ_e) and Ge<Ga, Sb, Ni, AK> ones with N^*_{Sb}=2.3·10^{15} cm^{-3} (μ^*_e). In complex doped crystal: N_{Sb}=5.1·10^{16}cm^{-3}, N_{Ga}=4.25·10^{16}cm^{-3}, N_{Ni}=3.1·10^{15} cm^{-3} and N_{AK}=2,05·10^{15} cm^{-3}. The signs are the experimental data. The dotted and solid lines are the calculated data. The solid lines are resulting mobilities μ_e and μ^*_e; dotted lines are mobilities at electron scattering on phonons (μ_f) and ions of the impurities (μ_i and μ^*_i).

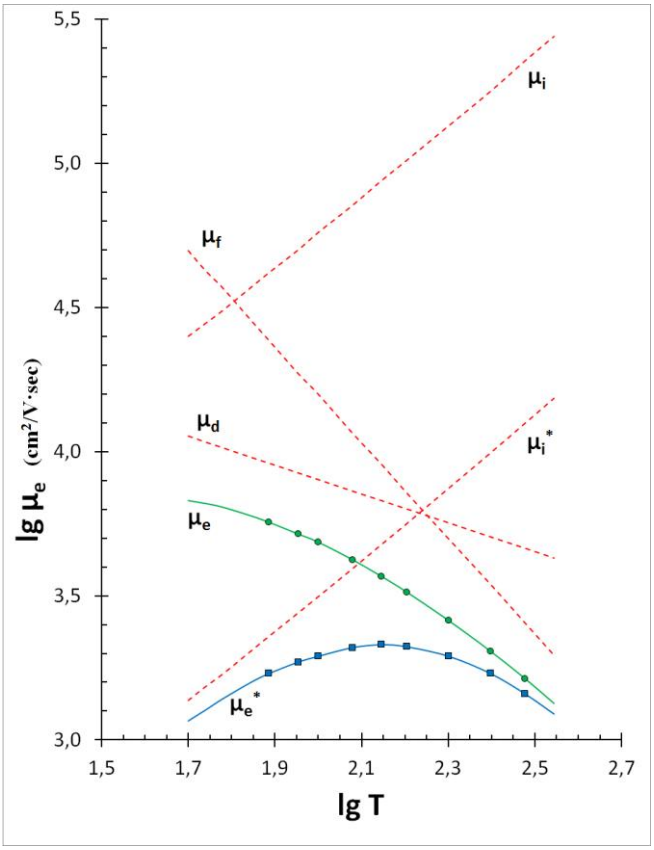


Fig.3. Temperature dependences of electron mobility in $Ge_{0.9}Si_{0.1}$<Sb> crystals with N_{Sb}=4.05·10^{15} см$^{-3}$ (μ_e) and $Ge_{0.9}Si_{0.1}$<Ga, Sb, Ni, AK> with N^*_{Sb}=3.1·10^{15} cm^{-3} (μ^*_e).In complex doped crystal N_{Sb}=3.55·10^{16}cm^{-3}, N_{Ga}=2.92·10^{16}cm^{-3}, N_{Ni}=2.18·10^{15} cm^{-3} and N_{AK}=1.95·10^{15} cm^{-3}. The signs are the experimental data. The dotted and solid lines are the calculated data. The solid lines μ_e and μ^*_e are resulting mobilities; dotted lines are mobilities at electron scattering on (μ_f) phonons, (μ_d) melt defects and (μ_i , μ^*_i) impurity ions.

In this connection the scheme presented in Fig.1A is put in foundation of interpretation of μ_e temperature dependence experimental data in crystals. In these crystals the electric conduction in investigated temperature region is carried out mainly because of Sb impurity ionization with effective concentration

$$N^*_{Sb} = N_{Sb} - (N_{Ga} + 2N_{Ni} + N_{AK}).$$

Fig.1B shows the characteristic temperature dependences of free electron concentration in such crystals on example of Ge and $Ge_{0.9}Si_{0.1}$ samples. As it is seen in the given temperature interval all Sb atoms in matrix are totally ionized in connection with enough small activation energy of this impurity (~0.01эВ [4]) and electron concentration in conduction band stays practically constant.

The results of μ_e temperature dependence experimental measurements in Ge and $Ge_{0.9}Si_{0.1}$ crystals correspondingly are presented by signs on fig.2 and 3. For comparison the dependences for both crystals doped by only Sb impurity with N_{Sb} concentrations and corresponding complex doped crystals with Sb effective concentrations of the same order are given on these figures. In spite of proximity of free electron concentrations in each from couples of Ge and $Ge_{0.9}Si_{0.1}$ crystals the electron mobility in them essentially differs. It is observed in low-temperature region.

The interpretation of experimental data by electron mobility in samples is carried out taking into consideration the fact that phonons and ions of impurities in Ge, in $Ge_{0.9}Si_{0.1}$ and melt disorders are the main scatering mechanisms of free charge carriers in considered temperature region [1,3]. It is known that electron mobility in Ge and Ge-like compositions Ge-Si at scattering on (μ_f) phonons in invesyigated region is the temperature power function and is described by following expression [3,4]:

$$\mu_f = A_x \cdot T^{-1.66} \qquad (1)$$

The mobility (μ_d) limited by electron scattering on melt disorders in solid solutions is also described by power dependence on T [1,3]:

$$\mu_d = B_x \cdot T^{-0.5} \qquad (2)$$

The coefficients A_x and B_x are constant for each composition and are the following: $A_0=4.9\times10^7$ for Ge [4], $A_{0.1}=3.35\times10^7$ and $B_{0.1}=8.0\times10^4$ for $Ge_{0.9}Si_{0.1}$ [4].

The electron mobility in matrix at scattering (μ_I) ion impurity is defined by Brooks-Herring formula [9] taking into consideration ion Coulomb field screening by free electrons:

$$\mu_i = \frac{64\pi^{1/2}\varepsilon^2(2kT)^{3/2}}{(\sum N_i Z_i^2)e^3 m_e^{*1/2}}\left[\ln\frac{24m_e^* k^2T^2\varepsilon}{e^2\hbar^2 n}\right]^{-1} \quad (3)$$

Here N_i and Z_i are concentration and charge state degree of each impurity and additional AC; ε is matrix dielectric constant; m_e^* is density effective mass of electron state. In concrete cases considered by us all Ga, Sb atoms and AC are in one-fold ionized state. Ni atoms in whole temperature interval are charged negatively with degree equal to 2 and their concentration is equal to Ni atoms substituting at *T* annealing [8].

The temperature dependences of electron mobility in samples at their scattering on phonons and impurity ions in Ge and in $Ge_{0.9}Si_{0.1}$ at their scattering on melt defects are shown by dotted lines in fig.2 and 3. The calculated curves of (μ_e) resulting electron mobility shown in figures by dotted lines are calculated by following formula based on additivity of different electron scattering mechanisms:

$$\frac{1}{\mu_e} = \frac{1}{\mu_f} + \frac{1}{\mu_d} + \frac{1}{\mu_i} \quad (4)$$

As it is seen these curves coincide with corresponding experimental data on electron temperature dependence in both sample couples. The analogous results are obtained by us for all Ge-like compositions of Ge-Si solid solutions.

CONCLUSION

Summarizing the obtained data of electron mobility in $Ge_{1-x}Si_x$ ($0\le x\le 0.13$) crystals complex doped by <Ga,Sb,Ni> impurities in which the additional AC appear, one can make the following conclusion: the experimental data on free electron mobility in $Ge_{1-x}Si_x$ <Ga, Sb, Ni> crystals in 77-300 K interval after sample thermal treatment at 1000 – 1050K well coincide with calculated ones taking into consideration the electron scattering on phonons, melt defects, fully ionized impurities Ga, Sb, Ni and also thermoinduced AC.

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