World Journal of Condensed Matter Physics, **2013, 3, 43-45**
http://dx.doi.org/10.4236/wjcmp.2013.31007 Published Online February 2013 (http://www.scirp.org/journal/wjcmp)

Intervalley Scattering of Electrons in n-Si at $T = 77 \div 450$ K

Valerii Ermakov[1], Volodymyr Kolomoets[1], Leonid Panasyuk[1], Baja Orasgulyev[2]

[1]V. Lashkaryov Institute for Semiconductor Physics NAS of Ukraine, Kiev, Ukraine; [2]Caspian State University, Aktau, Kazakhtan.
Email: ekol@isp.kiev.ua

Received October 9th, 2012; revised December 4th, 2012; accepted December 16th, 2012

ABSTRACT

The change in electron mobility of n-Si with increasing the temperature which may be due to the inclusion of gLO-phonon energy of 720 K, is presented. Under orientation of the uniaxial pressure X//[110]//J, g-transitions are attached in the directions [100] and [010]. The f-transitions are not completely removed from valleys located in the plane (100). In this case, there is no change in the slope of the dependence logρ vs. log$T$ for the temperature range 77 to 450 K. So, no appreciable contribution of g-transitions to intervalley scattering occurs, while the observed is the decisive role of f-transitions to intervalley scattering. The results of measuring of the tensoresistivity effect for n-Si crystals under X//[001]//J are presented at these temperatures too.

Keywords: Silicon; f-Transitions; g-Transitions; Tensoresistivity Effect; Uniaxial Strain

1. Introduction

Previously [1], the crucial role of f-transitions in intervalley scattering of electrons in n-Si with strong uniaxial pressures X//[001] and temperatures to 300 K was first demonstrated. In the same work, small contribution of g-transitions to this type of scattering was shown. It is unknown, however, whether the electron mobility wile change at $T > 300$ K, if there is the possibility of g-transitions, which, moreover, are not completely eliminated under strong uniaxial pressure X//[001].

The analysis of experimental data of many works on the study of f- and g-transitions in n-Si indicates that the discussion of their role in intervalley scattering is not finished until now. This is due to the fact that silicon possesses a sufficiently wide set of phonons, which can make sufficiently comparable contribution of electrons to the intervalley scattering [2-7].

The scattering between Δ_1 valleys that are aligned along the non-equivalent directions is caused by f-transitions. In these processes the phonons from Σ line are involved. According to the selection rules the TO- and LO-phonons with Σ_1 symmetry are involved. Electron-phonon scattering between the valleys that are aligned along Δ is named g-transitions. This scattering is caused by the transitions in which the phonons are involved. In silicon these are the LO-phonons of Δ_2' symmetry.

In [2] was determined that electron interaction with g-type phonons is approximately in one and a half lower and the interaction with the f-type phonons is nearly twice as powerful as previously reported [7]. However, for he equilibrium condition low-energetic transition with assistance of g-phonons are forbidden. The change in mobility with increasing temperature may be due to inclusion of intervalley scattering related with g-transitions. Their contribution can increase with increasing temperature as a result of gLO-phonon energy of 720 K, deformation potential constant of which is $\approx 7.5 \times 10^8$ eV/cm. We used the direction of uniaxial pressure X//[110]//J to change at $T > 300$ K g-value and f-transitions in intervalley scattering. In this orientation of the uniaxial pressure, g-transitions are attached in the directions [100] and [010]. Furthermore, with strong intervalley scattering in uniaxial pressures, f-transitions between valleys [001] and [100] and $[\bar{1}00]$; $[00\bar{1}]$ and [100] and $[\bar{1}00]$; [001] and $[0\bar{1}0]$ and [010]; and $[00\bar{1}]$ and $[0\bar{1}0]$ and [010] (**Figure 1**) are excluded, and thus their intensity as compared to that in unstrained crystals decreases. This type of experiment gives us confidence that if there is significant contribution of gLO-conversion to the intervalley scattering of electrons in silicon at $T = 77 \div 450$ K.

As known, "Intel Corporation" introduced n-MOS transistors with silicon uniaxial deformed in the direction [001] channels, thus increase the mobility of electrons around twice at $T = 300$ K [8,9]. This increase is due to removal of intervalley scattering related with f-transitions, thereby increasing the steepness of the current-voltage characteristics (CVC) and cutoff frequency of switching.

2. Experimental

For the investigation of the intervalley scattering of elec-

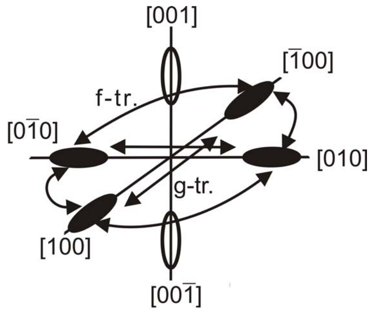

Figure 1. Scattering of electrons in n-Si for X//[110] X = 1.2 GPa.

trons in n-Si at $T = 77 \div 450$ K the specimens had sufficiently low donor concentration and namely 4×10^{13} cm^{-3}. Sample dimensions were $(0.7 \times 0.7 \times 10)$ mm^3 for longitudinal investigation geometry. In all the cases the quantity E don't over the limit of 0.5 V/cm. The accuracy of the X-ray method for determining the crystallographic orientation was ±15″. After mounting a sample on the experimental setup the precision of its orientation with respect to the applied stress was not less than ±30″. We used the installation for transport phenomena investigation under high uniaxial pressure described previously [10].

3. Results and Discussion

In this work we used the tensoresistivity (TR) effect at different directions of uniaxial pressure and temperature dependence of resistivity $\rho = \rho(T)$ in uniaxial deformed and undistorted crystal n-Si for the temperature range $T = 77 \div 450$ K. This temperature range covers the region of intrinsic conductivity of silicon crystals, so all conclusions about the impact of f- and g-transitions are limited to the temperature at which the intrinsic conductivity sets in.

Figure 2 presents the results of measuring the tensoresistivity effect for n-Si crystals under X//[001]//J at different temperature. The view of data dependencies shows that under uniaxial pressure X = 1.2 GPa at temperatures $T = 77 \div 450$ K, redistribution of carriers between valleys is completely finished, and the dependence of $\rho_X/\rho_0 = f(\mathrm{X})$ goes to saturation (curves 1 - 4). Clearly, the saturation function of $\rho(\mathrm{X})$ is characterized by lack absence of manifestations of f-transitions, and the possible presence of high gLO-temperature transitions in intervalley scattering. In the case of uniaxial pressure in the direction X//[001] the exponential law of changes in mobility $\mu \sim T^{-2,3}$ at X = 0 (**Figure 3** curve 1) and with strong uniaxial pressure X = 1.2 GPa - $\mu \sim T^{-1,6}$ (**Figure 3** curve 2) it has been shown. It is under this pressure the f-transition of intervalley scattering is completely removed, indicating their crucial contribution to the intervalley scattering at X = 0. Thus at X//[001] when the f-transitions are completely eliminated the slope of the lg μ - lg T dependence changes from −2.3 to −1.6.

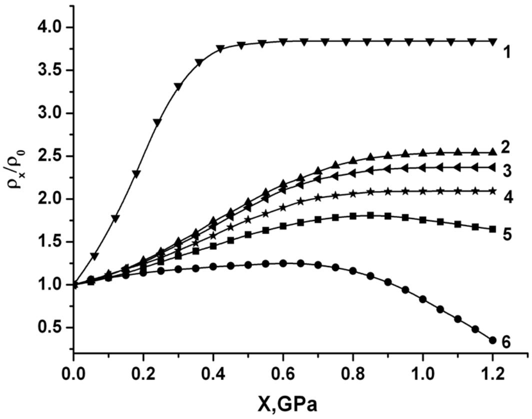

Figure 2. Dependence of $\rho_X/\rho_0 = f(\mathrm{X})$ in n-Si ($n_e = 4 \times 10^{13}$ cm^{-3}) for X//[001]//J at different temperatures: 1 - 77; 2 - 300; 3 - 320; 4 - 350; 5 - 400; 6 - 450 K.

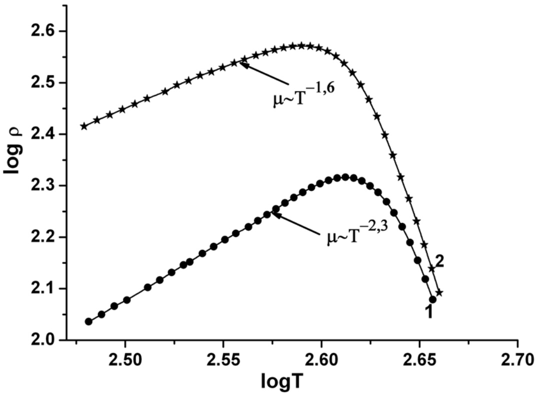

Figure 3. The dependence of $\rho = \rho(T)$ in double logarithmic scale in n-Si ($n_e = 4 \times 10^{13}$ cm^{-3}) for X//[001]//J: 1 – X = 0; 2 – X = 1.2 GPa.

For greater confidence in the decisive contribution of f-transition in intervalley scattering, we used the uniaxial pressure direction X//[110], in which the g-transitions in the directions [100] and [010] are added. Also, f-transitions are not completely removed, and f-transitions between valleys located in the plane (100) remain (**Figure 1**).

Figure 4 represents the results of measurements of the TR effect for n-Si crystals under X//[110]//J at different temperatures T, K.

In this case, there is no change in the slope of logρ vs. log$T$ dependence on the transition from the unstrained crystal n-Si to uniaxial-deformed. The value of this slope corresponds to the exponential law of changes in mobility $\mu \sim T^{-2,3}$ (**Figure 5**), indicating the absence of appreciable contribution of g-transitions in intervalley scattering of electrons and the presence of a decisive contribution to f-transition of intervalley scattering in temperature

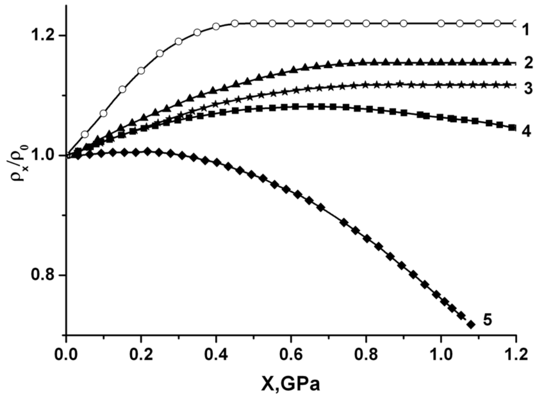

Figure 4. Dependence of $\rho_X/\rho_0 = f(\mathrm{X})$ in n-Si (n_e = 4 × 10^{13} cm^{-3}) for X//[110]//J at temperatures: 1 - 77; 2 - 300; 3 - 350; 4 - 400; 5 - 450 K.

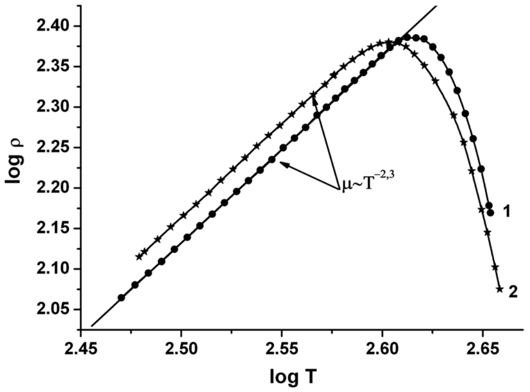

Figure 5. Dependence of $\rho = \rho(T)$ in double logarithmic scale for n-Si ($n_e = 4 \times 10^{13}$ cm^{-3}) for X//[110]//J: 1 − X = 0; 2 − X = 1.2 GPa.

range $T = 77 \div 450$ K.

4. Conclusions

The tensoresistivity effect in Si is experimentally studied at the temperatures $T = 77 \div 450$ K. It is shown that at X//[001] when the f-transitions are completely eliminated the slope of the lg μ - lg T dependence changes from −2.3 to −1.6. A significant change in the slope depending on μ vs. T in the pass from unstrained silicon $\mu \sim T^{-2,3}$ to uniaxial strained crystals $\mu \sim T^{-1,6}$ for X//[001] indicate a decisive contribution of f-transitions to intervalley scattering. In the case X//[110] at strong uniaxial strain 4 f-transitions and 2 g-transitions remain. The uniaxial stress does not change the slope of the lg μ - lg T dependence that points to the dominant contribution of f-transitions to the intervalley scattering.

We have established that the absence of changes in the slope of this relationship in the X//[110] indicates the absence of substantial contribution of g-transitions in intervalley scattering of electrons in this temperature range and the presence of decisive contribution of f-transitions to the intervalley scattering. Moreover for the equilibrium condition low-energetic transition with assistance of g-phonons are forbidden.

The uniaxial deformation can be also used to increase the mobility of electrons in the devices operated at $T >$ 300 K.

In the temperature range $T = 77 \div 450$ K at high temperature band for the temperature dependencies logρ − log$T$ the silicon intrinsic conductivity begins. Therefore, to determine the slope of logρ − log$T$ dependence, we use there a comparatively narrow temperature range.

REFERENCES

[1] P. I. Baranskii, I. V. Dakhovskii, V. V. Kolomoets, *et al.*, “Intervalley Scattering in n-Si for Temperature Range 78 - 300 K,” *Semiconductors*, Vol. 10, No. 8, 1976, pp. 1480 -1482.

[2] E. Pop, R. Dutton and K. E. Goodson, “Analytic Band Monte Carlo Model for Electron Transport in Si Including Acoustic and Optical Phonon Dispersion,” *Journal of Applied Physics*, Vol. 96, No. 9, 2004, pp. 4998-5005. doi:10.1063/1.1788838

[3] A. Sergeev, M. Y. Reizer and V. Mitin, “Deformation Electron-Phonon Coupling in Disordered Semiconductors and Nanostructures,” *Physical Review Letters*, Vol. 94, No. 13, 2005, Article ID: 136602. doi:10.1103/PhysRevLett.94.136602

[4] M. Ashe and O. G. Sarbei, “Electron-Phonon Interaction in n-Si,” *Physica Status Solidi B*, Vol. 103, No. 1, 1981, pp. 11-50. doi:10.1002/pssb.2221030102

[5] S. Zollner, J. Kircher, M. Cardona and S. Gopalan, “Are Transverse Phonons Important for Γ-X-Intervalley Scattering?” *Solid-State Electron*, Vol. 32, No. 12, 1989, pp. 1585-1589. doi:10.1016/0038-1101(89)90278-5

[6] S. Sinha, P. K. Schelling, S. R. Phillpot and K. E. Goodson, “Scattering of g-Process Longitudinal Optical Phonons at Hotspots in Silicon,” *Journal of Applied Physics*, Vol. 97, No. 2, 2005, Article ID: 023702. doi:10.1063/1.1831549

[7] R. Brunetti, C. Jacoboni, F. Nava, L. Reggiani, G. Bosman, *et al.*, “Diffusion Coefficient of Electrons in Silicon,” *Journal of Applied Physics*, Vol. 52, No. 11, 1981, pp. 6713-6722. doi:10.1063/1.328622

[8] S. Thompson, *et al.*, “A 90 nm Logic Technology Featuring 50 nm Strained Silicon Channel Transistors, 7 Layers of Cu Interconnects, Low k ILD, and 1 um^2 SRAM Cell,” *IEEE International Electron Devices Meeting*, *IEDM Technical Digest*, San Francisco, December 2002, pp. 61-64.

[9] T. Ghani, *et al.*, “A 90nm High Volume Manufacturing Logic Technology Featuring Novel 45nm Gate Length Strained Silicon CMOS Transistors,” *IEEE International Electron Devices Meeting*, *IEDM Technical Digest*, Washington, 8-10 December 2003, pp. 978-980.

[10] V. V. Kolomoets, V. N. Ermakov, B. A. Suss and V. E. Rodionov, “Installation for High Uniaxial Stress Generation,” Russian Patent No. 2040785, 1995.