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Physics

A Mechanism of Occurrence of a Negative Differential Conductivity in Pure p-Ge at Helium Temperatures

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ABSTRACT. The current-voltage characteristic of pure p-Ge in a pre-breakdown region of a shallow-level impurity breakdown has been estimated using Monte-Carlo simulation in the isotropic-parabolic and crimped dispersion law model approximations. It is shown that under conditions of crimped band dispersion a negative differential conductivity region is observed on the current-voltage characteristics, which is due to the light hole weighting phenomenon. *© 2008 Bull. Georg. Natl. Acad. Sci.*

Key words: *p-Ge, negative differential conductivity, crimped dispersion, impact ionization, Monte-Carlo simulation.*

The interest in p-Ge is essentially determined by strongly nonlinear phenomena observed at helium temperatures. One of these phenomena is the occurrence of a negative differential conductivity on the current-voltage characteristic in the pre-breakdown region of the shallow-level impurity breakdown. This phenomenon has repeatedly been studied in scientific works (see, e.g., [1-5]). However, so far there is no comprehensive theory explaining the whole range of experimental data.

In p-Ge with a complex band structure the mechanism of occurrence of a negative differential conductivity has not unambiguously been established. The conclusion that this phenomenon results from the non-monotonous dependence of the impact ionization coefficient is proposed in [1]. In [2], based on Monte-Carlo simulation, it is shown that the allowance for the inelastic scattering of shallow-level impurities leads to occurrence of a negative differential conductivity region. This conclusion is not consistent with the experimental results reported in [5] where in particular it is shown that in magnetic fields, weak for heavy holes but strong for light holes, the negative differential conduqtivity region disappears. This indicates unambiguously the strong effect of light holes on the process of occurrence of the negative differential conductivity.

The effect of the light hole band on p-Ge kinetic parameters has been studied in terms of the isotropic and parabolic band model in [6,7] where it is shown that in the region of intermediate fields [6,8] light holes play a significant role in formation of kinetic coefficients. However, the further studies showed the authors that this effect is not sufficient to explain the occurrence of the negative differential conductivity.

As is known, the light hole band is strongly non-parabolic [9]. Therefore, using Monte-Carlo simulation, a current-voltage characteristic was studied in terms of a crimped band model. The heavy hole band is strongly anisotropic, however, this does not markedly affect the kinetic parameters [9]. Proceeding from this fact, averaging was also performed during simulation in terms of the isotropic and parabolic band model.

The results of these studies are reported in the paper. In particular, it is shown that the negative differential conductivity region occurs with allowance for the non-parabolic dependence of the light hole dispersion law. The peculiarities of the mechanism of occurrence of the negative differential conductivity have been analyzed.

Monte-Carlo simulation was performed according to the classical scheme [10] for two different: (I) isotropic-parabolic and (II) crimped-band models.

For the differential impact ionization cross-sections the expression obtained in terms of the generalized Born theory was used [8, 11]. The differential cross-section of thermal recombination was determined by the revised Lax cascade theory [12, 13].

The current-voltage characteristic obtained by Monte-Carlo simulation (for lattice temperature - T=4.2K, acceptor concentration - N_a=15×10^{-12}cm^{-3} and compensation ratio - C=90%) is given in Fig. 1. The figure shows that both at band model (I) and (II) in the heating electric fields a superlinear dependence is observed which changes into a sublinear region. Unlike band model (I), in conditions of band model (II) the increase in the electric field results in saturation of the current-voltage characteristic with subsequent transfer into the negative differential conductivity region.

The results obtained can be analyzed in terms of the test particle model. As is known [3], in heating conditions in the heavy hole region the balance determines essentially the process of arrival from the light hole band and the energy relaxation processes. If we denote the concentration of heavy and light holes with energy ε, respectively, by $n_h(\varepsilon)$ and $n_l(\varepsilon)$, the intensity of arrival from the light hole band by $\omega_{l\to h}(\varepsilon)$ and the intensity of energetic relaxation by $\omega_\varepsilon(\varepsilon)$, in equilibrium conditions we obtain:

$$n_l \omega_{l\to h} = n_h \omega_\varepsilon \ . \qquad (1)$$

In the heating electric fields light holes are quickly heated and transfer into the light hole region due to interband transitions. At helium temperatures, in terms of band model (I), in the region of intermediate fields $\omega_{l\to h}(\varepsilon)$ exceeds $\omega_\varepsilon(\varepsilon)$ - the energy relaxation intensity $\omega_{l\to h}(\varepsilon) > \omega_\varepsilon(\varepsilon)$ [6, 7]. The holes transferred to the heavy hole band do not have time to relax the energy. The mobility of light holes exceeds essentially that of heavy holes. Hence, in the given energy region the contribution of light holes to the conductivity is sufficiently big. Both light and heavy holes take part in the ionization processes, which changes the ionization-recombination balance. As a result, a superlinear region appears on the current-voltage characteristics. With increasing electric

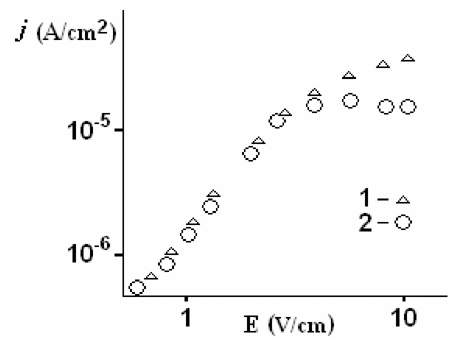

Fig. 1. Dependence of the current density on the applied electric field in p-Ge obtained from Monte-Carlo simulation for two different: 1. isotropic-parabolic and 2. crimped band models.

field, due to the scattering by optical phonons, the light hole concentration decreases. However, heavy holes have time to become heated. Therefore, in conditions of band model (I) only a sublinear dependence occurs and the transfer into the saturation region is not observed.

In case (II) a crimped band model, the light hole dispersion law differs from the parabolic model. With increasing energy light holes become heavier, which leads to the decrease in the intensity of arrival in the heavy hole band. This effect can become so significant that at high energies the interband inversion ($n_h < n_l$) occurs. The quantitative criterion of the interband inversion, with allowance for (I), takes the following form:

$$\omega_{l\to h} \le \omega_\varepsilon \ . \qquad (2)$$

It should be mentioned that in the literature there are examples of theoretical and experimental investigations of the interband inversion phenomenon in the absence of the magnetic field (heating-drift mechanism); however, they did not receive due attention.

At the interband inversion a mechanism of light hole accumulation occurs. In the conditions of scattering by optical phonons, this, in its turn, leads to a sharp decrease in the mobility, impact ionization coefficient and, hence, to a strong decrease in the sample conductivity. As a result, there occurs a negative differential region.

In the presented mechanism of occurrence of negative differential conductivity the light hole weighting phenomenon plays a significant role. The given analysis indicates the possibility of analytic study of a similar system in terms of the isotropic model with allowance for nonparabolic dispersion light hole dependence.

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(წარმოდგენილია აკადემიკოს გ. ხარაძის მიერ)

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REFERENCES

1. *S.W. Teitsworth, R.M. Westervelt, E.E. Haller* (1983), Phys. Rev. Lett., **51**: 825.
2. *W. Quade, G. Hüpper, E. Schöll, T. Kuhn* (1994), Phys. Rev. B, **49**: 1348.
3. *В.Ф.Банная, Л.И. Веселова, Е.М. Гершензон, В.А. Чуенков* (1976), ФТП, **10**: 338.
4. *В.Ф.Банная, Л.И. Веселова, Е.М. Гершензон, Е.М. Гурвич* (1976), ФТП, **10**: 452.
5. *В.Ф.Банная, Е.М. Гершензон, Л.И. Веселова* (1979), ФТП, **13**: 46.
6. *L. Kukutaria, G. Batsashvili* (2002), Bull. Georg. Acad. Sci., **166**, 1: 51.
7. *Z.Kachlishvili, L.Kukutaria, G. Batsashvili* (2002), In: Physics (TSU), **345**, 36-37: 133.
8. *Z.Kachlishvili, L.Kukutaria* (1997), Semiconductors, **31**, 9: 916.
9. *Э. Коннуэл* (1970), Кинетические свойства полупроводников в сильных электрических полях. М.
10. *C. Jacoboni, L. Reggiani* (1983), Reviews of Modern Physics, **55**, 3: 645.
11. *Л. А. Вайнштейн, И. И. Собельман, Е. А. Юков* (1979), Возбуждение атомов и уширение спектральных линий. М.
12. *В. Н. Абакумов, И. Н. Яссиевич* (1976), ЖЕТФ, **71**: 657.
13. *Т. О. Гегечкори, В. Г. Джакели, З. С. Качлишвили* (1981), Сообщ. АН ГССР, **163**: 565.
14. *Л. Е. Воробьев, С. Н. Данилов, В. И. Стафеев, В. Н. Тулупенко* (1987), ФТП, **9**: 1600.

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