CONFIGURATION OF ADIABATIC POTENTIALS OF DEEP IMPURITIES DISTINGUISHED BY PHONON ASSISTED TUNNELING IN FIR RADIATION FIELDS

S.D. Ganichev[a], W. Prettl
Institut für Experimentelle und Angewandte Physik, Universität Regensburg, D 93040 Regensburg, Germany

I.N. Yassievich
A.F. Ioffe Physicotechnical Institute, Russian Academy of the Sciences, St. Petersburg, 194021, Russia

Phonon assisted tunnel ionization of different on-site impurities in Ge and autolocalized DX^- centers in $Al_xGa_{1-x}Sb$ has been investigated in terahertz radiation fields. From field and temperature dependencies of ionization probability tunneling times for both types of impurities have been measured. It is shown that in one case the tunneling time is large and in the other smaller than the reciprocal temperature multiplied by a universal constant due to the different tunneling trajectories. This allows to distinguish in a direct way between the two types of configuration potentials of impurities in semiconductors.

Deep centers in semiconductors have been the subject of extensive studies. One of the aspects of investigations of deep impurities is the effect of an electric field on the thermal emission and capture of carriers. Emission and capture are of great importance for the kinetic and dynamic of semiconductors and for the investigation of electron-phonon interaction of deep centers. In particular, ionization or capture in an electric field are practically the only methods to find the parameters of multiphonon transitions which govern nonradiative processes associated with deep defects.

The insets in Fig. 1 presents two adiabatic potential diagrams with a shift in the configuration coordinate of the equilibrium position which correspond to electron-phonon coupling with (Fig. 1, bottom, right) and without (Fig. 1, top, left) autolocalization. The configuration of Fig. 1 (bottom, right) is usually assumed to apply to DX^- centers giving a big difference between ε_{opt} and ε_T [1,2]. The configuration of Fig. 1 (top, left) corresponds to on-site impurities. The details of the adiabatic potential configuration are of great importance for the non-radiative capture of free carriers. Here we demonstrate that tunnel ionization in terahertz fields [3] allows in a simple way a clear cut distinction between these types of potential configurations.

---

[a] on leave from A.F. Ioffe Physicotechnical Institute, Russian Academy of the Sciences, St. Petersburg, 194021, Russia

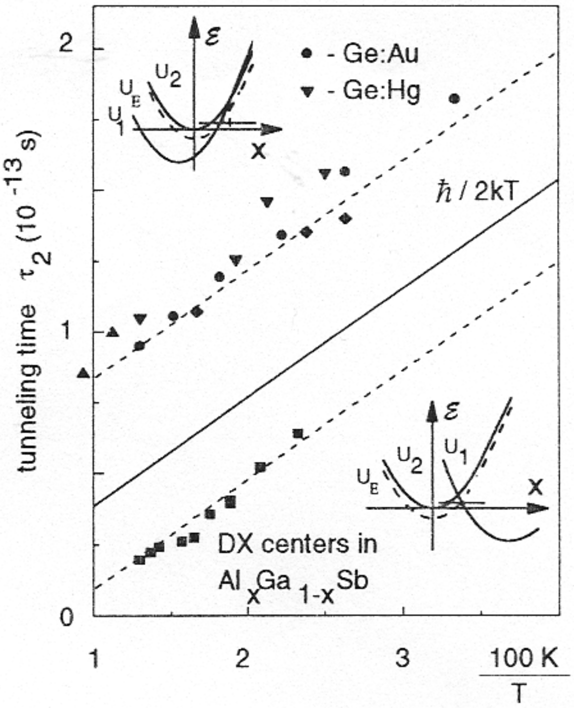

Fig. 1

It has been shown previously that the electric field of terahertz radiation leads to ionization of deep centers and acts like a dc field as long as the radiation frequency is smaller than the vibration frequency of the impurities [3]. In Fig. 1 the potential curves U_1 and U_2 correspond to the ground state and to the ionized center with zero kinetic energy of the charge carrier, respectively.

The impurities can be ionized by thermal excitation in the potential U_1 to an energy above the minimum of the ionized configuration U_2 and by tunneling from the bound configuration U_1 to U_2 [4]. In Fig. 2 the tunneling trajectories are plotted on an exaggerated scale for the two potential configurations shown in the insets of Fig. 1. In thermal equilibrium the multiphonon tunnel ionization rate is balanced by the capture of free carriers. In the presence of an electric field E the potential U_2 is shifted to lower energies as a whole (dashed curves in Fig. 1) yielding in semi-classical approximation an excess emission rate [4,5],

$$e(E) \propto exp(\frac{(eE)^2\tau_2^3}{3m^*\hbar}) \quad where \quad \tau_2 = \frac{\hbar}{2k_BT} \pm \tau_1 \tag{1}$$

is the tunneling time, caused by the re-arrangement of the lattice during detachment of the electron. The minus and plus signs correspond to DX and on-site impurities configurations, respectively. It can be shown that τ_1 is approximately the period of oscillations in U_1 and does not significantly depend on temperature and electric field. Eq. (1) shows that, due to different tunneling trajectories, on-site impurities and autolocalized centers may unambiguously be distinguished by the value of the tunneling time compared to the reciprocal temperature multiplied by universal constants.

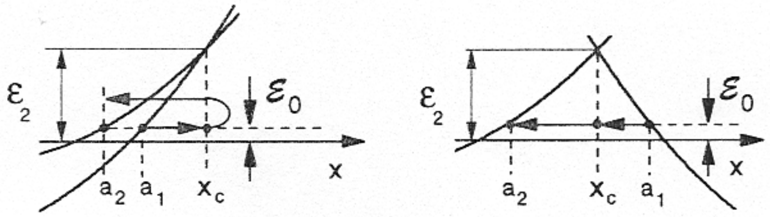

Fig. 2

The investigations of phonon assisted tunneling have been carried out on DX^- centers in $Al_xGa_{1-x}Sb$ (x= 0.25 and 0.5) [6] and on-site deep impurities Au, Hg, Cu, and Zn in Ge. Measurements have been carried out in the temperature range between 40 K and 90 K where the impurity centers are occupied in thermal equilibrium. The radiation source used was a pulsed far-infrared molecular laser optically pumped by a TEA CO_2 laser. Using NH_3 and D_2O as active gases, 40 ns pulses with a peak power of 100 kW have been obtained at wavelengths of 90.5 μm, 152 μm and 250 μm.

A photoconductive signal, depending nonlinearly on the radiation intensity, has been observed in all samples, at all wavelength and temperatures. The decay of signals is of the order of 100 ns for on-site impurities and hundreds of seconds in the case of DX^- centers, corresponding to known life times. The sign of the photoconductive signal indicates an increase in the free carrier concentration. These observations show that the signals are caused by the ionization of deep centers.

The probability of photoexcitation $e(E)/e_0 = \sigma_i/\sigma_d$ depends on the electric field of radiation, E, as $exp(E^2/E_c^2)$. The magnitude of the characteristic field E_c does not depend on the wavelength in the present spectral range between 90.5 μm and 250 μm but it is significantly smaller for lower temperatures. The same behaviour has been observed for on-site impurities. As it has been shown in [3], the fact that the photoconductivity is independent on the wavelength, the exponential dependence of the ratio of irradeated and dark conductivity, σ_i/σ_d, on the square of the electric field of the radiation and the variation of the signal with temperature permit to conclude that free carriers are generated by phonon assisted tunnel ionization [3-5] of deep centers with far infrared radiation. Using the experimental determined square of characteristic field E_c^2 which is according to (1) equal to $(3m^*\hbar)/(e^2\tau_3^2)$ we have calculated the tunneling time τ_2 as a function of temperature.

In Fig. 1 τ_2 of DX$^-$ center in Al$_x$Ga$_{1-x}$Sb, x=0.5 and on-site deep acceptors in germanium is plotted versus the reciprocal temperature 1/T. For the purpose of comparison Fig. 1 contains also a $\hbar$/2kT curve. In both cases τ_2 is of the order of $\hbar$/2kT and follows the 1/T temperature dependence. The data in Fig. 1 unambiguously demonstrates that τ_2 is larger than $\hbar$/2kT for an on-site impurity, however, it is smaller than $\hbar$/2kT for the DX$^-$ centers. This result clearly proves that autolocalized and on- site impurities may be distinguished by the tunneling time being determined from phonon assisted tunneling in terahertz fields.

Acknowledgments

Financial support by the Deutsche Forschungsgemeinschaft is gratefully acknowledged.

References

1. D. V. Lang and R. A. Logan, *Phys. Rev. Lett.* **39**, 635 (1977).
2. D. V. Lang, R. A. Logan and M. Jaros, *Phys. Rev.* B **19**, 1015 (1979).
3. S. D. Ganichev, W. Prettl, and P. G. Huggard, *Phys. Rev. Lett.* **71**, 3882 (1993).
4. V. N. Abakumov, V. I. Perel, and I. N. Yassievich, *Nonradiative Recombination in Semiconductors* edited by V. M. Agranovich and A. A. Maradudin, Modern Problems in Condensed Matter Sciences Vol. 33 (North Holland, Amsterdam, 1991).
5. S. D. Ganichev, I. N. Yassievich, and P. G. Huggard, *Semicond. Sci. and Technol.* **11**, 679 (1996).
6. B. K. Meyer, G. Bischopink, K. W. Benz, A. Schöner, and G. Pensl, *J. of Crystal Growth* **128**, 475 (1993).