Adiabatic Potentials Distinguished by Tunneling in FIR Radiation Fields.

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Abstract

Tunnel ionization of semiconductor deep impurities has been investigated in the field of FIR radiation where photon energies are much smaller than the binding energies. Applying pulsed lasers, substitutional on-site impurities and autolocalized DX$^-$ centers have been studied. It is shown that adiabatic potentials of small and large lattice relaxations may unambiguously distinguished by measured tunneling times.

Deep centers in semiconductors have been the subject of extensive studies. They are essential in control of the electronic properties of semiconductor materials. Deep impurities can reduce the conductivity by trapping carriers or compensating shallow impurities and can act as nonradiative recombination centers reducing the life time of free carriers. 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.

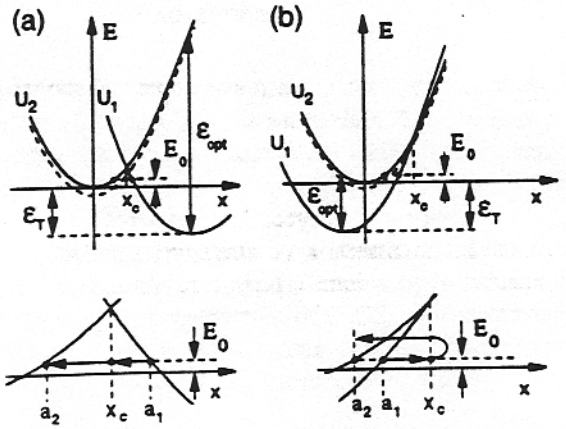


Fig. 1 presents two adiabatic potential diagrams with a shift in the configuration coordinate of the equilibrium position which correspond to electron-phonon coupling with (Fig. 1 (a)) and without (Fig. 1 (b)) autolocalization. The configuration of Fig. 1 (a) is usually assumed to apply to DX$^-$ centers giving a big difference between ε_{opt} and ε_T[1,2]. The configuration of Fig. 1 (b) 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 the two types of potential configurations shown in 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 deep impurities [3]. In Fig. 1 the 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 tunnelling from the bound configuration U_1 to U_2 [4]. 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]

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

where τ_2 is the tunnelling time, caused by the re-arrangement of the lattice during detachment of the electron. The minus and plus signs correspond to Fig. 1 (a) and (b), 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.

The investigations of phonon assisted tunnelling have been carried out on DX$^-$ centers in $Al_xGa_{1-x}Sb$ (x= 0.25 and 0.5) [5] 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.

The photoconductive signal strongly nonlinear with the radiation intensity has been observed in all samples, at all wavelength and temperatures. The kynetic of signals is of the order of 100 ns for on-site impurities and hundred of seconds in the case of DX centers. It corresponds to known life times. It The sign of the photoconductive signal indicates an increase in the free carrier concentration. These observations shows that the signal is caused by the ionization of deep centers.

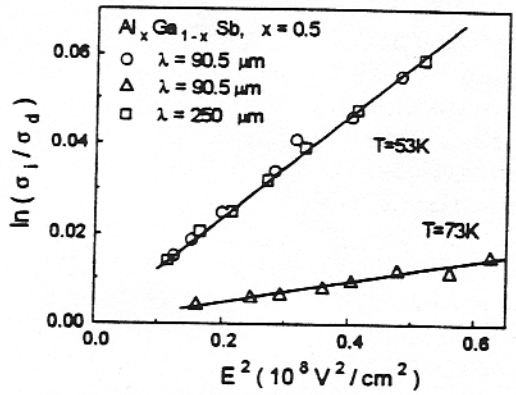
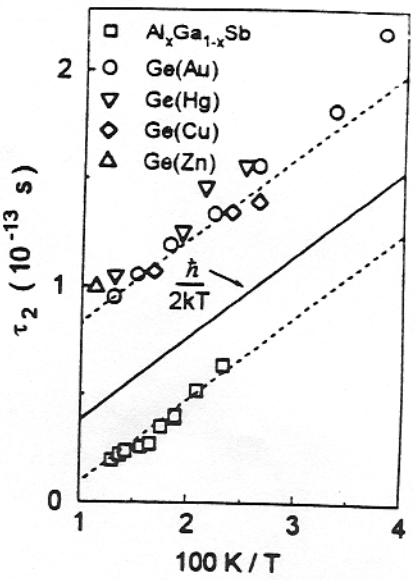


Fig. 2 shows the dependence of $\ln(\sigma_i/\sigma_d)$ on the square of the amplitude of the optical electric field for $Al_xGa_{1-x}Sb$ for two different wavelengths and temperatures, where σ_d and σ_i are the dark and irradiation induced conductivities of the sample, respectively. In Fig. 2 it is seen that the probability of photoexcitation $e(E)/e_0=\sigma_i/\sigma_d$ depends on the electric field as $\exp(E^2/E^2_c)$. 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] this observation rules out such a mechanisms of nonlinear optical carrier generation like multiphoton transitions light impact ionization, photon assisted tunnelling which all show a characteristic wavelength dependence. The fact that the photoconductivity is independent on the wavelength, the exponential dependence of 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 [4] of deep centers with far infrared radiation.

Using the experimental determined square of characteristic field E^2_c which is according to (1) equal to $(3m^*\hbar)/(e^2\tau_2{}^3)$ we have calculated the tunnelling time τ_2 is calculated as a function of temperature.



In Fig. 3 τ_2 of DX^- center in $Al_xGa_{1-x}Sb$, x=0.5 and on-site deep acceptors in germanium is plotted versus the reciprocal temperature 1/T. For the purpose of comparison Fig. 3 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 representation of Fig. 3 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 the autolocalized and on-site impuruties may be distinguished by the tunnelling time being determined from phonon assisted tunnelling in terahertz fields. Even small change in τ_2 may be resolved because the emission probability depends exponentially on the third power of the tunnelling time. The tunnelling time reflects the structure of the potential barriers which are systematically distinct for both potential configurations discussed here.

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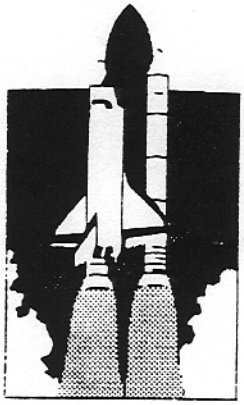

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