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DIRECT TUNNEL IONIZATION OF DEEP IMPURITIES IN THE ELECTRIC FIELD OF FAR-INFRARED RADIATION.

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Ionization of semiconductor deep impurity centers has been observed in the far infrared where photon energies are several factors of ten smaller than the binding energy of the impurities. It is shown that the ionization is caused at high intensities by direct tunnel ionization in the electric field of the high power radiation. This optical method allows the investigation of the tunnelling process at electric bias fields well below the threshold of avalanche breakdown.

Keywords: C. impurities in semiconductors, D. photoconductivity and photovoltaic, D: tunnelling

Tunnel ionization of deep impurities in semiconductors has been extensively studied applying static electric fields [1-6]. The emission and capture of carriers in high electric fields is of great importance for the kinetics and dynamics of semiconductors. In particular the properties of semiconductor microstructures may be affected by tunnelling of carriers in space charge regions of mesoscopic dimensions where the electric field may assume very high values. Ionizing impurities in static electric fields usually drives the system into avalanche breakdown which in many cases yields self-sustained periodic and even chaotic oscillations disguising the elementary process of tunnelling. Here we report on the first observation of direct tunnelling ionization of deep impurities in the electric field of a powerful far-infrared radiation.

A photoconductive signal increasing nonlinearly with irradiation power has been observed in gold and mercury doped *p-type* germanium where the photon energy is several factors of ten less than the binding energy of the impurities. The experimental results give evidence that the ionization of the impurities is due to a tunnelling emission of the holes into the valence band. The tunnelling potential is diminished by the electric field of the radiation. Tunnelling takes place within one period of terahertz field if the attractive impurity potential adiabatically follows the oscillation of the radiation field. In a previous study we have shown that such transitions may occur due to the phonon assisted tunnelling and may be detected for moderate radiation intensities of about 400 kW/cm^2 [7]. Measurements at higher intensities are presented which show the transition from the phonon assisted process to direct tunnelling without any thermal activation. As far as we know, this cold ionization of deep impurities [1, 2] has not yet been detected, neither in static electric fields. Photoionization of deep impurities in the radiation field of a far-infrared laser represents a method to investigate the tunnelling ionization of impurities in a range of electric fields well below the threshold of avalanche breakdown. The intrinsically high sensitivity of photoconductivity allows to study the tunnelling process with only a few carriers involved.

The binding energies of *Au* and *Hg* in *Ge* are E_i~150 meV and 90 meV respectively [1]. The deep acceptor density in the investigated *p-type Ge* materials was in the range of 10^{14} cm^{-3} to 10^{15} cm^{-3}. The samples were placed in an optical cryostat with the temperature being variable between 20-77 K. In this temperature range

practically all charge carriers were frozen into the impurity ground states. The photoconductive signal was measured using a standard load resistor R_l=50Ω circuit, taking care that the bias voltage at the sample was substantially below the threshold of electric avalanche breakdown. The radiation sources used were pulsed FIR NH_3 and CH_3F molecular lasers optically pumped by a TEA CO_2 laser providing 40 ns pulses. The measurements were carried out at the wavelengths λ, of 90.5 μm, 152 μm and 250 μm. The corresponding photon energies are 13.7 meV, 8.2 meV and 5 meV being much smaller than the ionization energies of the impurities. The maximum intensity of radiation in the sample was 2 MW/cm^2. For varying the intensity calibrated teflon attenuators have been used. The intensity incident on the sample has additionally been controlled by a fast photon drag detector. Cold and warm black polyethylene, quartz and teflon filters were used to reject visible light and thermal background radiation.

A photoconductive response was found at all three wavelengths. The sign of the photoconductive signal corresponds to a decrease in sample resistance. The decay time of the observed signal was about 50 ns for *Ge(Hg)* and 80 ns for *Ge(Au)*, i.e. somewhat longer than the laser pulse. As it has been shown previously [7] the photoconductivity is a result of the photoionization of deep impurities by light with $\hbar\omega << E_i$.

The observed signal is a strongly nonlinear function of the intensity I. Below a certain value I^* of the intensity the voltage follows the relation $V \sim \exp(I/I_c)-1$ due to phonon assisted tunnelling [7]. The characteristic intensities I_c and I^* depend significantly on the binding energy of the impurities and the temperature getting larger at higher temperatures. Rising the radiation intensity above I^* leads to a slower increase of the signal. This change in the character of the nonlinearity occurs at higher intensities I^* for deeper impurities and higher temperatures. Both impurities show this nonlinear dependence of the signal on intensity at all three wavelengths. As an important result, for a given irradiation intensity, the signal does not depend on the wavelength in the present spectral range between 90.5 μm and 250 μm. As it has been shown in [7] this observation rules out other mechanisms of nonlinear optical excess carrier generation like multiphoton transitions [8, 9], light impact ionization [10] or photon assisted tunnelling [11].

Deep impurities may be thermally ionized by multiphonon processes if the energy of phonons is less than the impurity binding energy. The presence of a sufficiently strong electric field increases the thermal emission rate of free carriers by tunnelling processes. A further increase of the electric field strength leads to the direct electron tunnel ionization. This mechanisms will be discussed within the adiabatic approximation. Fig. 1 shows the adiabatic potentials as a function of a configuration coordinate x in terms of the Lukovsky model [1]. Curves U_1 and U_2 correspond to the bound state of the hole at the center and the ionized center, respectively. The transition of holes from U_1 to U_2 is favoured when the configuration coordinate is close to the crossing point x^* of both potential curves. This requires the rather high energy of $\varepsilon_T + \varepsilon_c$ where ε_T and ε_c. are defined in Fig. 1. Therefore thermal ionization usually proceeds via tunnelling of the impurity from curve U_1 to curve U_2 at a vibration energy only slightly exceeding the thermal binding energy, ε_T [1, 2]. In the presence of an electric field hole tunnelling enhances this process because the final state is now reduced in energy. This leads in Fig. 1 to the potential curve U_ε, corresponded to the negative kinetic energy of a hole, located below the term U_2. The higher the electric field strength, the greater is the decrease of the term U_ε with a corresponding increase in hole tunnel rate and ionization probability. Because the radiation frequency used in our experiments is less than the impurity vibrational frequency (in the order of the optical phonon frequency), this adiabatic model may be applied assuming tunnelling in the electric field of the radiation.

At high fields, the bottom of the potential curve U_ε drops below the bottom of the curve U_1 (U_f in Fig. 1) which leads to direct tunnelling of the electrons from U_f to U_1 without assistance of phonons. The necessary field for this process is [1]:

$$E > E^* = (2m\varepsilon_T)^{1/2} / \tau_2 \qquad (1)$$

when the energy of the emitted electrons ε_0 becomes larger than the thermal binding energy ε_T. Here m and τ_2 are the effective mass of the involved hole and the tunnelling time, respectively. The tunnelling time τ_2 depends on the temperature as [1, 2, 7]

$$\tau_2 = \hbar / 2kT + \tau_1 \qquad (2)$$

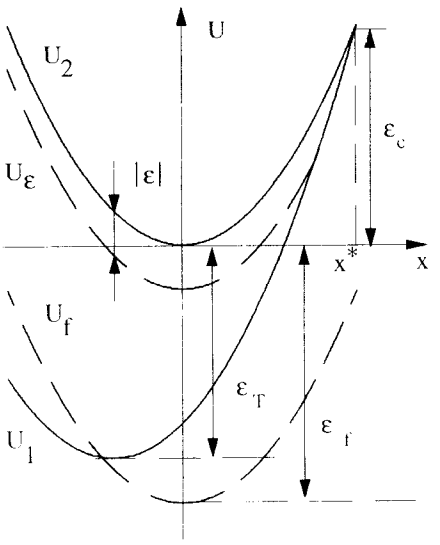

Fig. 1. Schematic representation of the adiabatic potentials as functions of a configuration coordinate of impurity motion, x. ε_T is the thermal binding energy. Solid curves U_1 and U_2 correspond to the hole bound to the center and detached from the impurity at the bottom of the valence band ($\varepsilon = 0$), respectively. The dashed curve U_ε and U_f are the potential curves of the ionized impurity in a weak and strong electric field, correspondingly.

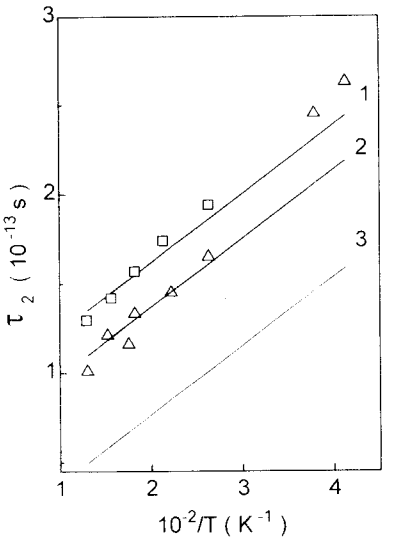

Fig. 2. The tunnelling time τ_2 of *Ge(Au)* (triangels) and *Ge(Hg)* (squares) experimentally determined following the method suggested in [7] as a function of reciprocal temperature. The full lines show calculations after $\tau_2 = \tau_1 + \hbar / 2kT$ with τ_1 equal to $8 \cdot 10^{-14}$ s (line 1), $6 \cdot 10^{-14}$ s (line 2), and 0 (line 3).

where $\hbar / 2\tau_1$ is of the order of the phonon energy. Following the method suggested in [7], the tunnelling time has been experimentally determined as function of temperature. The results are shown in Fig. 2 for the impurities gold and mercury. It is seen from Eq.1 that cold ionization requires higher electric fields for deeper centers as well as for higher temperatures due to the temperature dependence of the tunnelling time. It can be shown [2] that the probability of cold ionization as a function of the electric field strength E rises slower with increasing field than the phonon assisted tunnelling rate. Furthermore phonon assisted tunnelling saturates at high electric fields when U_f approaches the potential U_1 of the bound state. Thus at high fields the emission rate of holes is dominated by cold ionization.

The experimentally determined dependence of $\ln(\sigma_i/\sigma_d)$ on the square of the amplitude of the optical electric field is shown for *Ge(Au)* (doping density $7 \cdot 10^{14}$ cm^{-3}) in Fig. 3 and for *Ge(Hg)* (doping density $4 \cdot 10^{14}$ cm^{-3}) in Fig. 4. Here σ_i and σ_d are the conductivity of the sample under the irradiation and in the dark. In figures measurements are plotted for different temperatures obtained at the wavelength λ = 90.5 μm. Because the duration of the light pulses is shorter than the lifetime of nonequilibrium carriers in *p-Ge*, recombination may be ignored during the optical excitation. Therefore the experimentally determined relative photoconductivity, $(\sigma_i - \sigma_d)/\sigma_d$ is equal to $\Delta p/p$ where p is the free carrier concentration and σ_i/σ_d corresponds to the optical ionization probability normalized by the thermal ionization probability without radiation. It is seen from the insets in Figs. 3 and 4 that at relatively small fields the probability of photoexcitation depends on the electric field like $\exp(E^2/E_c^2)$ and that the characteristic field E_c increases significantly with the temperature. It agrees to the temperature dependence of the tunnelling time τ_2 in Eq. 2.

Increasing the field above the characteristic field E^* leads to a slower increase of the photoconductive signal with rising electric field (Figs. 3 and 4). Thus E^* may be identified with the field of the experimentally observed intensity I^*. Because the sample impedance (>10 kΩ) is much higher than the load resistance (50 Ω) and $\Delta\sigma/\sigma_d$ for $E = E^*$ is significantly different for different temperatures

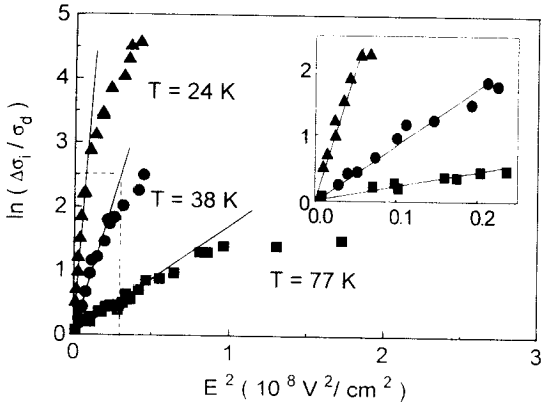

Fig. 3. The dependence of $\ln(\sigma_i/\sigma_d)$ for *Ge(Au)* (E_i~150 meV) at three different temperatures on the square of the amplitude of the optical electric field E at wavelength λ = 90.5 μm ($\hbar\omega$ = 13.7 meV). The inset shows the range of small electric fields corresponding to the area bordered by broken lines.

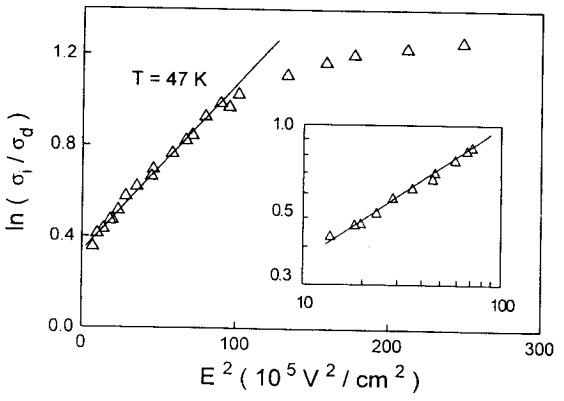

Fig. 4. The dependence of $\ln(\sigma_i/\sigma_d)$ for *Ge(Hg)* (E_i~90 meV) at T=47K on the square of the amplitude of the optical electric field E at wavelength λ = 90.5 μm ($\hbar\omega$ = 13.7 meV). The inset shows the range of small electric fields.

(Fig. 3) this change in the intensity dependence of photoconductivity can not be attributed to saturation of the signal. It is found that the characteristic field E^* increases linearly with rising temperature as expected from Eq. 1 and Eq. 2. The experimental results also show that the change to a slower increase of σ_i/σ_d as a function of E^2 occurs at higher intensities for deeper center. The weaker increase of ionization with rising electric field and the dependence of the characteristic field E^* on both the temperature and impurity binding energy permits to conclude that direct hole tunnelling takes place for $E > E^*$. The absolute values of characteristic fields E^* obtained are three times smaller than the same values calculated according to Eq. 1. This is a fairly good agreement in view of the crudeness of the underlying model which ignores details of the band structure like nonparabolicity, warping etc.

In summary, we have observed the photoionization of deep impurity centers in a semiconductor by far-infrared radiation with quantum energies much smaller than the impurity ionization energy. This is attributed to ionization by phonon assisted tunnelling and, at high intensities, direct tunnel ionization in the field of the high-power radiation. The high sensitivity of photoconductivity allows to study the tunnelling process, and to determine tunnelling times, with only a few carriers involved at electric bias fields well below the threshold of avalanche breakdown.

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