High-frequency regime of electron tunneling

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Abstract A drastic enhancement of the terahertz tunneling ionization of deep impurities in semiconductors has been observed in the high frequency limit of $\omega\tau_e \gg 1$ (ω is electric field frequency and τ_e is the tunneling time). For a given constant tunneling rate an increase of frequency by a factor of seven leads to a drop of the required electric field strength by three orders of magnitude. It is shown that the enchancement of tunneling ionization is due to the fact that electrons can absorb energy from the radiation field during tunneling reducing the effective width of the tunneling barrier.

1 Introduction

In [1] we have shown that the increase of the frequency of an alternating electric field leads to an enhancement of tunneling ionization of deep impurities as compared to static fields if $\omega\tau_2$ approaches one, τ_2 is the tunneling time of redistribution of the defect vibrational system being equal to electron tunneling time τ_e [2]. Here we report on investigations of tunneling ionization of deep impurities for much larger values of $\omega\tau_2$ where a drastical increase of the tunneling probability is observed with rising of $\omega\tau_2$.

2 Theoretical consideration

The ionization of deep impurities in an electric field is achieved by two simultanious tunneling processes, the tunneling of the defect, with probability P_d, and electron tunneling through the triangular potential barrier formed by the impurity potential well and the electric field (see inset in Fig. 1), with probability P_e. The defect ionization is accomplished by thermal excitation of the system in the adiabatic bound state potential U_1 to a vibrational energy $\mathcal{E}_1$ and tunneling of the impurity configuration from this state into the ionized configuration U_2 [3]. The application of an electric field $E = E_0\cos(\omega t)$ leads to electron tunneling. Thus, electrons can be emitted at a negative kinetic energy $-\varepsilon$ which shifts the adiabatic potential of the ionized configuration U_2 to a lower energy and, hence, increases the ionization probability.

The ionization probability is given by:

$$e(E) = \int\!\!\int P_e P_d \exp(-\mathcal{E}_1/k_BT)d\varepsilon d\mathcal{E}_1. \qquad (1)$$

The probability of the defect tunneling in the semi-classical approximation is [4,3]:

$$P_d \propto \exp(-2(S_2 \mp S_1)) \qquad (2)$$

where $S_{1,2}$ is the principal function of defect tunneling under the potential $U_{1,2}$ multiplied by $i/\hbar$ [4] .

The probability of electron tunneling is [5,1]:

$$P_e \propto \exp(-2S_e(\varepsilon)) \qquad (3)$$

with

$$S_e(\varepsilon) = -\frac{\varepsilon}{\hbar}\int_0^{\tau_e}\frac{1}{\gamma^2}\sinh^2(\omega\tau)d\tau + \frac{\varepsilon\tau_e}{\hbar}. \qquad (4)$$

Here $\gamma \equiv \sqrt{2m^*\varepsilon}\,\omega/eE$ and $\tau_e = \hbar\partial S_e/\partial\varepsilon$ has the meaning of an electron tunneling time [6].

At high temperatures and not very high electric field strengths, so that the electron energy ε is smaller than the defect vibration energy $\mathcal{E}_1$, the ionization is caused by phonon assisted tunneling. The electron tunneling time τ_e is equal to $\tau_2 = \hbar\partial|S_2|/\partial\mathcal{E}_1|_{\varepsilon=0}$, the time of defect tunneling under the potential U_2, and the field dependence of the ionization probability is given by [1],

$$e(E) \propto \exp\left[\frac{E^2}{(E_c^*)^2}\right] \quad \text{with} \quad (E_c^*)^2 = \frac{3m^*\hbar}{e^2(\tau_2^*)^3} \qquad (5)$$

$$\text{where} \quad (\tau_2^*)^3 = \frac{3}{4\omega^3}(\sinh(2\omega\tau_2) - 2\omega\tau_2). \qquad (6)$$

$$\text{and} \quad \tau_2 = \hbar/2kT \pm \tau_1. \qquad (7)$$

Here $\tau_1 = \hbar\partial|S_1|/\partial\mathcal{E}_1|_{\varepsilon=0}$ is the time of defect tunneling under the potential U_1 and signs + and - correspond to adiabatic potentials configuration of autolocalized and substitutional impurities, correspondently [2].

With increasing electric field strength or lowering temperature, so that $\varepsilon \gg \mathcal{E}_1$, the direct carrier tunneling from the ground state into the continuum becomes dominant [3]. This leads to a weaker field dependence of the ionization probability and decreases the tunnelling time with rising E. Thus at high field strengths $\omega\tau_2$ becomes smaller than one and the frequency dependence of tunneling vanishes.

3 Experimental results and analysis

The measurements have been carried out on Au, Hg and Cu doped Ge and on DX^- centers in $Al_{0.5}Ga_{0.5}As$:Te in the temperature range where at thermal equilibrium practically all carriers are bound ($T = 4.2-150$ K). Terahertz electric fields have been applied using a high power line-tunable optically pumped NH_3 FIR-laser [3]. Electric field strengths up to about 40 kV/cm ($\simeq 5$ MW/cm^2) could be achieved in the frequency range from 3 to 50 THz with 40 ns pulses. Irradiation of the samples with FIR-radiation leads to ionization of impurities which is detected by photoconductivity. The ratio of irradiated conductivity and dark conductivity is $\sigma_i/\sigma_d \propto e(E)/e(0)$ [3].

At sufficiently high temperatures (e.g. $T = 50 - 100$ K) and in the investigated frequency range, the ionization probability of all materials is observed to be independent on the radiation frequency and increases with

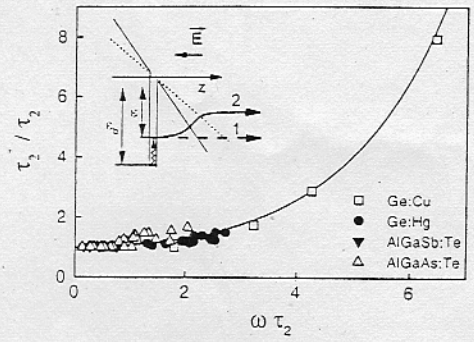

Fig. 1 Ratio τ_2^*/τ_2 as a function of $\omega\tau_2$. The line shows the calculations after Eq. 6 Inset: Electron tunneling trajectory in (1) a static and (2) an alternating electric field.

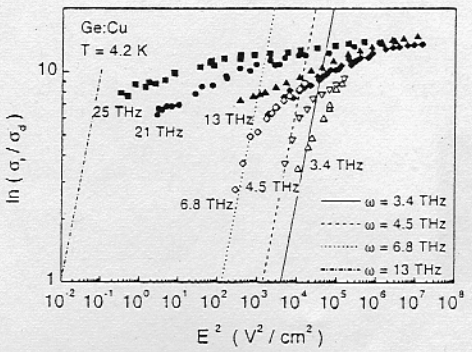

Fig. 2 Dependence of $\ln(\sigma_i/\sigma_d)$ on E^2 of Ge:Cu at 4.2 K. Straight lines show the dependence according to Eq. (1) - (4) for four lowest frequencies used in experiment.

rising E like $\exp(E^2/E_c^{*2})$. Thus, the ionization is due to phonon assisted tunneling in the quasi–static regime (Eq. (5), (6) with $\omega\tau_2 \ll 1$). The electron tunnels at the momentary magnitude of the electric field in a time shorter than the period of oscillation and the electric field acts like a static field (see inset in Fig. 1) [2,3, 7]. The frequency independent tunneling is limited to $\omega\tau_2 \simeq 1$.

Lowering the temperature leads to an increase of τ_2 (Eq. (7)) and thus $\omega\tau_2$ becomes larger than one. In this case the ionization probability is observed to be still depended exponentially on E^2, but the magnitude of E_c^* decreases strongly with increasing frequency. Varying the temperature and the radiation frequency the dependence of the effective time τ_2^* has been obtained from measured values of E_c^*. In Fig. 1 the ratio τ_2^*/τ_2 determined experimentally is plotted as a function of $\omega\tau_2$ and compared to calculations after Eq. (5). In contrast to static electric fields where the electron tunnels at a fixed energy, in alternating fields the energy of the electron is not conserved during tunneling (see inset in Fig. 1). In this case the electron can absorb energy from the field, which leads to a sharp increase of the tunneling probability with rising frequency.

Further decrease of the temperature leads to a much stronger frequency dependence of the ionization probability due to the fact that at e.g. 4.2 K and at low field strengths the condition $\omega\tau_2 \gg 1$ is valid for the whole frequency range investigated here. Such a drastic frequency dependence, which is observed for all samples, is shown in Fig 2 for Ge:Cu at 4.2 K. It is seen that at relatively low field strength for a given constant signal a change of six orders of magnitude of E^2 needs only a seven times change in frequency ω. In order to display in one figure the total set of data covering eight order of magnitude in the square of the electric field, $log(E^2)$ has been plotted on the abscissa. To make a easy comparison to the $exp(E^2/E_c^2)$ dependence of σ_i/σ_d possible, a *log log* presentation has been used for the ordinate. For the three lowest frequencies $\omega = 3.4$ THz, $\omega = 4.5$ THz and $\omega = 6.8$ THz and not to high electric field strengths, the ionization probability can be described in terms of phonon assisted tunneling $e(E) \propto \exp(E^2/E_c^{*2})$ as it was the case for all frequencies at higher temperatures (the lines in Fig. 2).

However, at higher field strength the field dependence of the emission probability is much weaker and the frequency dependence practically disappears. This effect is the result of the transition from phonon assisted tunneling to direct tunneling without involving phonons which is characterized by a weaker growth of the ionization probability in comparison to the field dependence of phonon assisted tunneling [3]. The calculations after Eq. (1-4) for Ge:Cu at 4.2 K and for the frequencies used in the experiments taking into account both processes, phonon assisted tunneling and direct tunneling, shows that the theory describes qualitatively well all experimentally observed features of the field and frequency dependence of tunneling ionization. The disappearance of the frequency effect at very high fields can be explained by the electric field dependence of the tunneling time τ_2. In the high field regime the defect tunneling trajectory is shifted to lower energies $\mathcal{E}_{1\varepsilon}$ leading to a decrease of τ_2. By this $\omega\tau_2$ becomes smaller than one and the frequency dependence vanishes.

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