Magnetic field effect on tunnel ionization of deep impurities by terahertz radiation

S.D. Ganichev[1], S.N. Danilov[1], M. Sollinger[1], J. Zimmermann[1],
A.S. Moskalenko[2], V.I. Perel[2], I.N. Yassievich[2], C. Back[1] and W. Prettl[2]

[1] Universität Regensburg, D 93040 Regensburg, Germany
[2]A.F.Ioffe Physico-Technical Institute, St. Petersburg, Russia

Abstract: A suppression of tunnelling ionization of deep impurities in terahertz frequency electric fields by a magnetic field is observed. It is shown that the ionization probability at the external magnetic field, B, oriented perpendicular to the electric field of terahertz radiation, E, is substantially smaller than that at $B \parallel E$. The effect occurs at low temperatures and high magnetic fields.

Overview

Tunneling ionization of deep centers in the terahertz field of high-intensity far-infrared laser radiation, with photon energies tens of times lower than the impurity binding energies has been investigated in great detail during the last decade [?]. In contrast to tunneling ionization of atoms, where only electron tunneling takes place, ionization of impurities in solids is accomplished by two simultaneous processes: electron tunneling through the potential well formed by the attractive force of the impurity and the externally applied electric field and the redistribution of the vibrational system by defect tunneling. At very high radiation electric field strengths direct tunneling may occur without involving phonons.

The tunneling probability is independent of radiation frequency up to very high frequencies. In this quasi-static regime, electrons tunnel at constant energy in a time much shorter than the reciprocal radiation frequency ω^{-1}. At higher frequencies, however, tunneling probability drastically increases in comparison to the tunneling in dc field of the same field strength. In such a high-frequency regime electrons can absorb energy from the radiation field during tunneling leaving the barrier at higher energy. By this the effective width of the tunneling barrier is reduced and thus, the tunneling probability enhanced.

In a semiclassical approach defect tunneling occurs from the adiabatic potential of the impurity bound state to one where the carrier is detached from the impurity. The tunneling probability is controlled by the Büttiker-Landauer tunneling time τ being a function of temperature. The transition from frequency independent tunneling in a classical electric field to fully quantized multi-photon transitions takes place in the terahertz range [?] and may be explored applying high-power THz lasers. The borderline is given by $\omega\tau = 1$ where ω is the radiation frequency.

These considerations are based on semiclassical theory where the carriers have a classical trajectory. In this case the tunneling probability is expected to be affected by the strength and the orientation of an external magnetic field. For electron tunneling through static potential barriers this effect was theoretically investigated in [?] and observed in quantum well structures [?]. The theory has been extended for phonon-assisted tunneling ionization of deep impurities in dc electric fields [?] and in high frequency alternating fields [?, ?] showing that also in the case of phonon-assisted tunneling, even in high-frequency regime, the carrier emission is suppressed by an external magnetic field ($B \perp E$). In this work we give evidence for the applicability of the semiclassical model to tunneling assisted by phonons which is concluded from the experimental observation of the supression of tunneling probability by an external magnetic field oriented perpendicular to the carrier trajectory.

Tunneling in alternating fields

The probability of phonon assisted tunneling depends on alternating electric field strength as [?]

$$e(E) \propto \exp\left[\frac{E^2}{(E_c^*)^2}\right] \quad \text{with} \quad (E_c^*)^2 = \frac{3m^*\hbar}{e^2(\tau^*)^3} \qquad (1)$$

and

$$(\tau^*)^3 = \frac{3}{4\omega^3}(\sinh(2\,\omega\tau) - 2\,\omega\tau) \qquad (2)$$

The frequency dependence of the tunneling process is controlled by $\omega\tau$ with τ depending on temperature like $\tau = \hbar/2kT \pm \tau_1$. Here τ_1 is of the order of the period of the impurity vibration and plus and minus correspond to substitutional and auto-localized impurities, respectively.

In the presence of an external magnetic field oriented perpendicular to the electric field of radiation the functional dependence of the probability on the electric field strength remains unchanged, however the value of effective time τ^* gets magnetic field strength dependent. Increase of the cyclotron frequency $\omega_c = eB/m^*$ over the reciprocal tunneling time results in the decrease of the tunneling probability. The suppression of the tunneling probability occurs in both frequency ranges, at low frequencies when tunneling is independent of frequency as well as at high frequencies when the tunneling probability increases drastically with

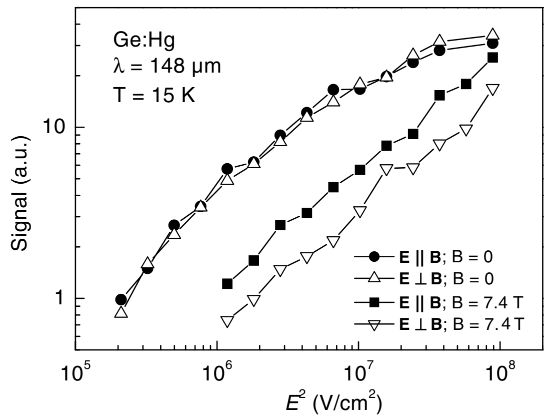

Figure 1: Photoconductive signal for Ge:Hg as a function of E^2 for different magnetic field strength and orientations.

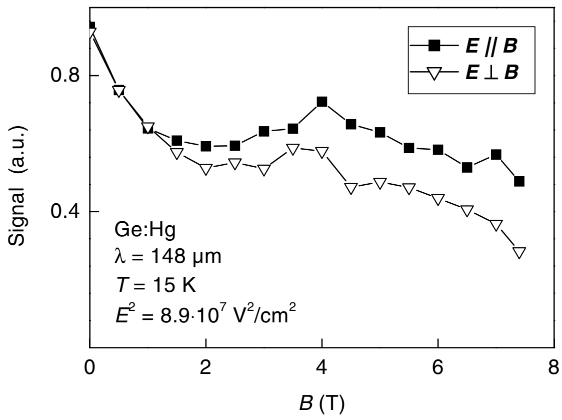

Figure 2: Photoconductive signal as a function of magnetic field strength for two $E \perp B$ and $E \parallel B$.

rising frequency. The effect of a magnetic field B on tunneling is strongest if it is oriented normal to the radiation electric field E and vanishes if $B \parallel E$.

Experimental and Results

The experiments were carried out on mercury doped germanium in the temperature range from 10 K to 70 K. Tunneling ionization has been achieved by far–infrared laser radiation with photon energies much smaller than the thermal impurity ionization energy $\varepsilon_T = 90$ meV. The ionization probability has been measured by detecting photoconductivity [?]. The radiation source applied was a pulsed far-infrared molecular laser optically pumped by a TEA–CO_2 laser. Operating the optically pumped laser with NH_3 and CH_3F as active gases, 40 ns pulses with intensity up to 2 MW/cm^2 have been obtained at wavelength of 148 μm and 496 μm. An external magnetic field up to 7.5 T has been applied. The ionization probability has been measured for $E \parallel B$ and $E \perp B$ as a function of the radiation intensity $I \propto E^2$ for different magnetic field strengths. In addition the magnetic field dependence of the signal has been determined for constant intensity. The orientation between external magnetic field B and electric field of linearly polarized terahertz radiation E has been changed by means of a $\lambda/2$ crystal quartz plate.

In Fig. 1 the dependence of the photoconductive signal being proportional to the ionization probability on the square of the electric field strength of the radiation is plotted for $B = 0$ and $B = 7.4$ T. These measurements show that at zero magnetic field the ionization probability is independent on the electric field orientation. At high magnetic fields, however, the signal for $E \perp B$ drops significantly below that of $E \parallel B$. This suppression of the tunneling probability is also be seen in the magnetic field dependence of the photoconductive signal shown in Fig. 2.

The effect of tunneling suppression occurs only at low temperatures where, on the one side, practically all carriers are frozen out on the impurities and on the other side the tunneling time assumes high values [?]. At high temperatures the effect of free carrier absorption interferes with the change of conductivity by tunneling ionization therefore no suppression of the signal could be observed. Tunneling suppression has been observed in both regimes, the quasi-static limit ($\omega\tau < 1$) at 496 μm and in the high-frequency limit ($\omega\tau > 1$) obtained by the excitation with radiation of 148 μm.

In summary, our present observation shows that for $B \perp E$ the magnetic field deflects the carriers, which increase the tunneling trajectory. Thus, a magnetic field reduces the ionization probability when the cyclotron frequency becomes larger than the reciprocal tunneling time. Experimental findings are in a good agreement with the developed theory of phonon-assisted tunneling ionization of deep impurities in the presence of a magnetic field.

References

[1] S.D. Ganichev, I.N. Yassievich, and W. Prettl, J. Phys.: Condens. Matter **14**, R1263-R1295 (2002)

[2] L.V. Keldysh, Zh. Eksp. Teor. Fiz. **47**, 1945 (1964) [Sov. Phys. JETP **20**, 1307 (1965)].

[3] L.P. Kotova, A.M. Perelomov, and V.S. Popov, Sov. JETP **27**, 616 (1968).

[4] L. Eaves, K.W.H. Stevens, and F.W. Sheard, *Tunnel currents and presence of an applied magnetic field*, in: *The physics and fabrication of microstructures and microdevices*, editors M.J. Kelly and C. Weisbuch, p. 343, Springer-Verlag, Berlin 1986.

[5] V.I.Perel, I.N.Yassievich, JETP Lett. **68**, 804 (1998).

[6] A.S. Moskalenko, S.D. Ganichev, V.I. Perel, and I.N. Yassievich, Physica B **273-274**, 1007 (1999).

[7] A.S. Moskalenko, V.I. Perel, and I.N. Yassievich, JETP **90**, 217 (2000).