Hole tunnelling from beryllium acceptors in GaAs

1997 J. Phys.: Condens. Matter 9 L557

(http://iopscience.iop.org/0953-8984/9/39/004)

J. Phys.: Condens. Matter **9** (1997) L557–L559. Printed in the UK PII: S0953-8984(97)85975-9

LETTER TO THE EDITOR

Hole tunnelling from beryllium acceptors in GaAs

A Dargys, N Žurauskienė and K Bertulis
Semiconductor Physics Institute, A Goštauto 11, 2600 Vilnius, Lithuania

Received 14 July 1997

Abstract. We present experimental results on the field ionization of beryllium acceptors in micrometre AlGaAs/GaAs structures on a nanosecond timescale. At liquid helium temperature, the tunnelling ionization of beryllium was found to switch on effectively at electric fields higher than 5000 V cm^{-1}.

Recently, the first observation of field ionization of acceptors in epitaxial GaAs was reported, in [1, 2]. The light holes were found to determine the acceptor-to-valence-band tunnelling dynamics in the case of carbon acceptors. The participation of lattice phonons in the tunnelling process was found to be negligible at liquid helium temperature; however, at higher temperatures the acoustic phonons were found to enhance the tunnelling rate, although their influence was not strong. Below, experimental results on the field ionization of beryllium in GaAs under experimental conditions similar to those of [1, 2] are presented.

The samples were grown by the molecular-beam epitaxial technique. The layer investigated, of thickness 2 μm, was grown on the conducting p^+ substrate and doped with beryllium at a concentration of about 10^{16} cm^{-3}. On the top of this, an $Al_{0.25}Ga_{0.75}As$ barrier of thickness 0.1 μm and, finally, a layer 1.5 μm thick of heavily doped (acceptor concentration $\approx 5 \times 10^{18}$ cm^{-3}) p^+-GaAs, to provide the electrical contact, were grown. The barrier precluded the flow of dc current, and allowed the fast transient currents that were associated with the tunnelling ionization of beryllium to be revealed. Earlier, for this purpose [1, 2], we used n^+p junctions. The samples were mesa shaped, with the useful area of 0.12 mm^2. To induce the transient currents caused by field ionization of beryllium and the drift of free holes out of the 2 μm layer, a fast ramped voltage was applied between the upper p^+ layer and the substrate. Four samples were investigated which, apart from minor differences, gave similar results.

Curve 1 in figure 1 shows the time dependence of the voltage drop over the sample, while curves 2–4 show the resulting transient currents, at room, liquid nitrogen and liquid helium temperatures, respectively. At room temperature, all of the beryllium atoms are thermally ionized, and the transient current density can be approximated by the formula

$$J(t) = aC_b \Bigg/ \left(1 + 2\frac{at}{eNd_b}C_b\right) \tag{1}$$

which follows from Poisson's equation in the variable-width depletion layer approximation. The formula describes the transient current due to the growth of a depletion layer near the barrier. In (1), a is the rate of increase of the voltage V over the sample at the time t, $a = \mathrm{d}V/\mathrm{d}t$. N is the uncompensated majority-acceptor concentration. d_b and C_b are the apparent thickness and capacitance of the barrier. Because of the frozen space charge in the barrier and the presence of the initial depletion layer near the barrier, the apparent

0953-8984/97/390557+03$19.50

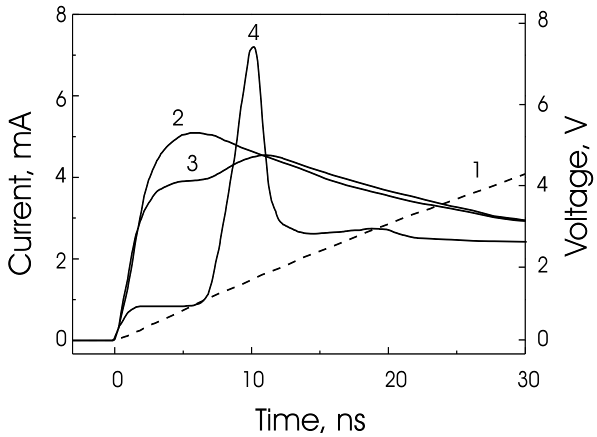

Figure 1. The voltage over (curve 1) and transient currents through (curves 2, 3, 4) the $Al_{0.25}Ga_{0.75}As$/GaAs:Be sample at three lattice temperatures: (2) 300 K; (3) 77 K; (4) 4.2 K.

barrier thickness may be larger than the geometrical one. The initial fronts t_F of curves 2 and 3 are influenced mainly by the barrier capacitance. Using $t_F \approx 3$ ns and taking into account the fact that the load resistance was 47 Ω, we calculated that at room temperature $C_b \approx 2.5 \times 10^{-8}$ F cm^{-2}. Assuming that $d_b = \epsilon/C_b$ and that the dielectric permittivity of the apparent barrier is $\epsilon = 1.1 \times 10^{-10}$ F m^{-1}, from the decreasing part ($t > 5$ ns) of curve 2, we found using (1) that $N = 2.8 \times 10^{16}$ cm^{-3}. Hence, the estimated beryllium concentration is close to that expected from the sample growth conditions.

Curve 3 in figure 1 shows the transient current after cooling the sample to liquid nitrogen temperature. The reduction of the current in the first ten nanoseconds is thought to be related to a freeze-out of a proportion of the free holes onto deep capture centres in the barrier or AlGaAs/GaAs interface. Curve 4 shows the transient current in the same sample at liquid helium temperature. The shape of the curve is similar to the one found earlier in [1, 2] for carbon-doped p-type GaAs samples: at first one observes the capacitive current plateau, on which a sharp tunnelling peak caused by the field ionization of neutral beryllium acceptors appears later. Due to the higher doping level, in the present case the tunnelling peaks are higher. The capacitive current in the first moments, $I_C = 0.8$ mA, gives the sample capacitance 5.3 pF, which is close to the calculated one, 6.5 pF, for the 2 μm dielectric layer of GaAs. It should be noted that at liquid helium temperature the initial front is limited by the experimental set-up rather than the sample barrier capacitance.

Figure 2 shows the evolution of the tunnelling peaks as the voltage ramping rate is increased. The arrows on the curves indicate the moments at which the electric field in the sample reached the value of 5 kV cm^{-1}. The field distribution at this moment in the 2 μm layer is close to uniform. From this figure it follows that the ionization of beryllium in GaAs is insensitive to the voltage growth rate and starts up at an electric field strength similar to that for carbon acceptors. This is not surprising since the ionization energies of beryllium (28 meV) and carbon (26 meV) are similar. However, it should be noted that the present results were obtained at a doping level higher by an order of magnitude, and with samples having active-region lengths five times shorter. Computer simulation [3] based on the formalism described in [4] showed that at the doping level of 10^{16} cm^{-3} the development of the tunnelling peak after the tunnelling process has been switched on is very fast and is strongly influenced by the self-forming space-charge region near the barrier. For

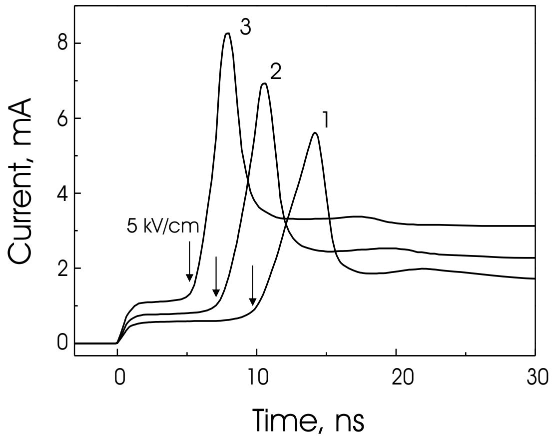

Figure 2. The transient current for various voltage growth rates dU/dt: (1) 1.06×10^8 V s^{-1}, (2) 1.47×10^8 V s^{-1}, (3) 2.04×10^8 V s^{-1}. The arrows indicate the moments at which the electric field in the active layer of the sample reaches 5 kV cm^{-1}.

this reason, purer samples are preferable for measuring the tunnelling parameters from the tunnelling peaks, since at lower doping levels the space charge of ionized acceptors will have a smaller influence on the overall shape of the tunnelling peaks. We have also made some preliminary measurements of the temperature dependence of the tunnelling rate by the method described in [2]. As in the case of GaAs:C_{As} we found rather weak growth of the tunnelling rate as the lattice temperature was increased above liquid helium temperature. This indicates that at temperatures close to that of liquid helium, the phonons play only a small role in the field ionization of beryllium acceptors as well.

In conclusion, quantum mechanical tunnelling of holes from isolated beryllium acceptors was observed for micrometre length $Al_{0.25}Ga_{0.75}As$/GaAs:Be samples on a nanosecond timescale. The tunnelling process was found to switch on very effectively when the value of the ramped electric field exceeded 5 kV cm^{-1}.

References

[1] Dargys A and Žurauskas S 1995 *J. Phys.: Condens. Matter* **7** 2133
[2] Dargys A, Kudžmauskas Š and Žurauskas S 1995 *J. Phys.: Condens. Matter* **7** 8967
[3] Dargys A and Žurauskas S 1997 unpublished results
[4] Dargys A, Žurauskienė N and Žurauskas S 1990 *Phys. Status Solidi* b **162** 183