Lithuanian Journal of Physics, Vol. **44**, No. 4, pp. 263–266 (2004)

HOT CARRIERS IN TUNNEL DIODE

S. Ašmontas [a,b], J. Gradauskas [a,c], J. Paukštė [b], V. Petkun [a], D. Seliuta [a], A. Sužiedėlis [a,c], E. Širmulis [a], and G. Valušis [a,c]

[a] *Semiconductor Physics Institute, A. Goštauto 11, LT-01108 Vilnius, Lithuania*
[b] *Kaunas University of Technology, Panevėžys Institute, Klaipėdos 3, LT-35209 Panevėžys, Lithuania*
[c] *Vilnius Gediminas Technical University, Saulėtekio 11, LT-10223 Vilnius, Lithuania*
E-mail: jonas@pfi.lt

Received 27 January 2004

We present the first results of experimental study of free carrier heating in a degenerate semiconductor when the carriers were excited by CO_2 laser light and microwave radiation of 10 and 35 GHz. Tunnel GaAs $p-n$ diodes were used as objects under investigation. It is shown that the carrier heating reduces the dark tunnel current, while at high enough forward bias the thermo-diffusive current is responsible for the formation of the signal. The magnitude of the electromotive force arising under the microwave irradiation depends linearly on the power and increases with the decrease of the semiconductor lattice temperature. It is nearly independ of the microwave frequency.

Keywords: hot carriers, degenerate semiconductor, tunnel diode, infrared radiation, microwaves

PACS: 07.57.Kp, 73.40.Gk, 78.70.Gq

1. Introduction

Carrier heating by external electromagnetic radiation in moderately doped semiconductors has been widely investigated during last decades [1]. It is established that an electromotive force (emf) arises due to carrier heating in inhomogeneous semiconductors [1, 2]. The hot carrier emf U_T originates because of the change of mobility and diffusion coefficients under the influence of strong electric field. Investigations of the hot carrier emf show that the magnitude of U_T is directly proportional to the potential barrier height of a $p-n$ junction [1, 3]. Therefore, in order to increase the sensitivity of a sensor operating on the basis of carrier heating in the inhomogeneous structures, it is necessary to increase the carrier concentration in n- and p-regions of the $p-n$ junction. But the increase of doping level leads to the degeneration of electron and hole gases. A semiconductor becomes degenerate when the carrier concentration exceeds critical value N_C determined as

$$N_\mathrm{C} = \frac{2}{h^3}(2\pi m^* kT_0)^{3/2}, \qquad (1)$$

where m^* is the electron effective mass, h and k are Planck's and Boltzmann constants, respectively, and T_0 represents the semiconductor lattice temperature. Thus, the degeneracy of the regions close to the abrupt $p-n$ junction leads to the carrier tunnelling, i. e. the nature of carrier flow across the junction changes substantially, namely, the injection current is replaced by the tunnel one.

Since the invention of the nonresonant tunnel $p-n$ diodes, especially of the backward ones, they are widely used to detect microwave radiation (see, for instance, [4]). However, their operation is mainly based on the rectification of high frequency currents due to the asymmetry of $I-V$ characteristic.

In this communication we investigate the ways of carrier flow across the tunnel $p-n$ junction when the carriers are heated by the microwave and infrared radiation.

2. Samples and experimental technique

The investigated tunnel diodes were fabricated on the base of epitaxial GaAs structures grown by molecular beam epitaxy on semiinsulating GaAs substrates. The thickness of p^+- and n^+-layers was 0.4 and 0.6 μm, respectively. High carrier densities ($p^+ = 5{\cdot}10^{19}$ cm^{-3} and $n^+ = 3{\cdot}10^{18}$ cm^{-3}) as well as an abrupt doping profile were achieved using amphoteric nature of silicon on the (311) GaAs surface. The samples were etched as 120×120 μm^2 mesas with evap-

ISSN 1648-8504

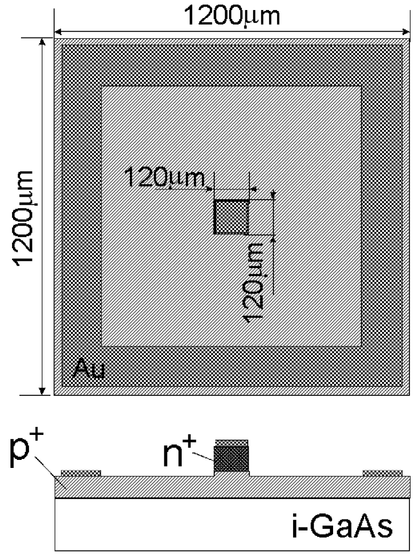
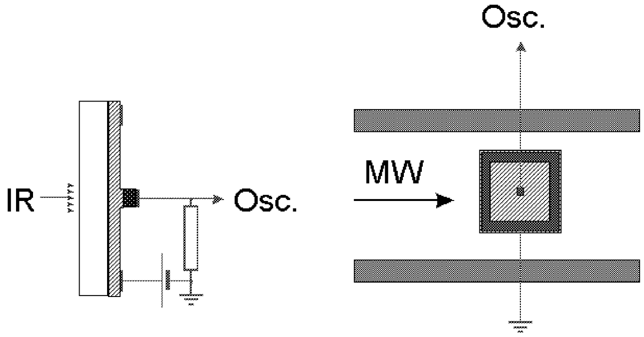


Fig. 1. Schematic view of the tunnel diode: $n^{+} = 3{\cdot}10^{18}$ cm^{-3} and $p^{+} = 5{\cdot}10^{19}$ cm^{-3}; $h_{n^+} = 600$ nm and $h_{p^+} = 400$ nm are thicknesses of the respective epitaxial layers.



(a) (b)

Fig. 2. Measurement schemes under (a) infrared and (b) microwave excitation.

orated and annealed Ni–Au–Ge metal contacts on the top (see Fig. 1).

Short pulses of infrared and microwave radiation were applied in order to avoid the crystal lattice heating. As a source of infrared radiation we used the Q-switched CO_2 laser with 10.6 μm wavelength, 200 ns pulse duration, and 40 Hz repetition rate. Maximum intensity was about 1.2 MW/cm^2. The $p{-}n$ junction was illuminated from the substrate side. Figure 2(a) shows the measurement circuit.

In the case of microwave excitation the tunnel diode was placed inside the waveguide in such a way that the electric field was parallel with the $p{-}n$ junction plane (see Fig. 2(b)). Magnetrons generating microwave pulses of 10 and 1 kW power at 10 and 35 GHz frequencies, respectively, were used as microwave radi-

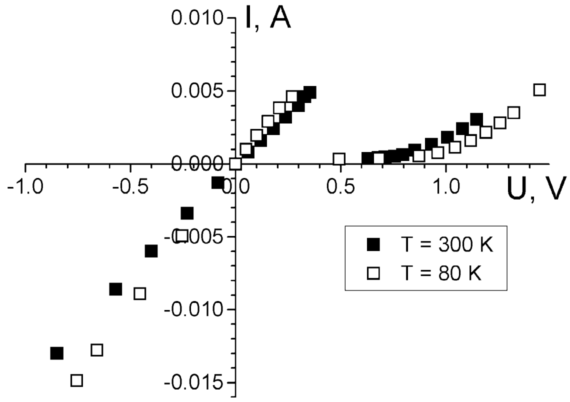


Fig. 3. Dark voltage–current characteristics of the tunnel diode at room and liquid nitrogen temperatures.

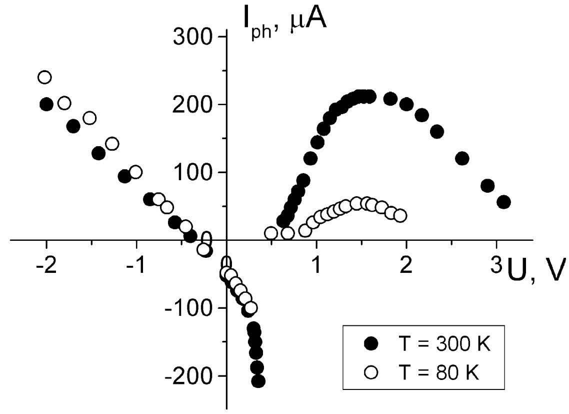


Fig. 4. The dependence of photocurrent on applied bias voltage at room and liquid nitrogen temperatures. The diode is illuminated with the CO_2 laser light.

ation sources. The measurements were performed at room and liquid nitrogen temperatures.

3. Experimental results and discussion

Dark current–voltage characteristics of the tunnel $p{-}n$ junction measured both at room and at liquid nitrogen temperatures are presented in Fig. 3. It is worth noting that the tunnel current increases with the decrease of the lattice temperature. As known [5], the tunnel current across the junction can be expressed as

$$I = A\frac{eU}{4kT_0}(E_C - E_V)^2, \tag{2}$$

where A is a constant, U stands for bias voltage, E_C and E_V represent conduction and valence band edges, respectively. Comparison of the theory with the experimental measurements shows sufficient qualitative agreement.

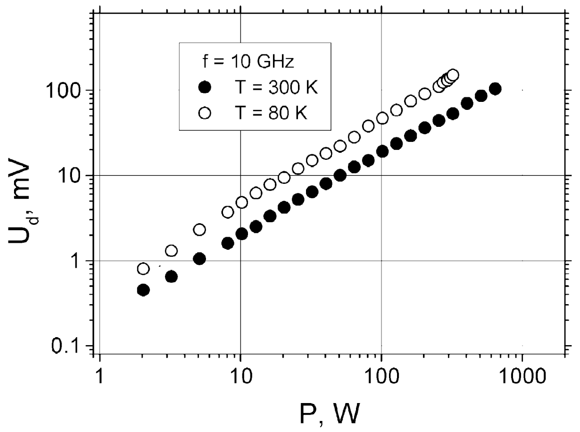


Fig. 5. The photosignal across the diode versus incident microwave power at room and liquid nitrogen temperatures. Microwave frequency is 10 GHz.

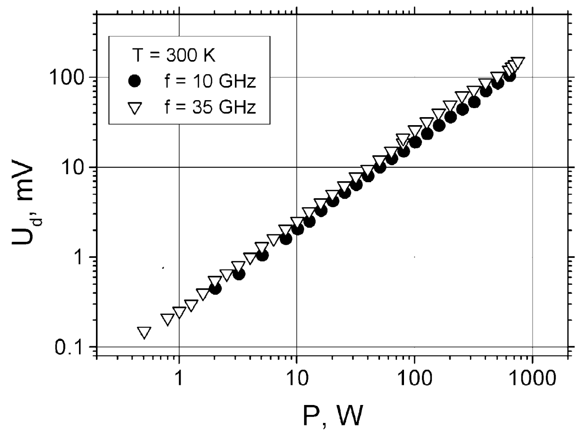


Fig. 6. The photosignal across the diode versus incident microwave power at 10 and 35 GHz frequencies measured at room temperature.

Illumination of the tunnel p–n junction with the CO_2 laser radiation causes the decrease of the dark tunnel current. The dependence of the photocurrent on bias voltage is depicted in Fig. 4. At reverse and low forward bias values the photocurrent monotonically changes with the bias voltage. At higher values of the forward bias the direction of the photocurrent abruptly changes. This indicates that at higher forward bias values the current across the diode increases under the illumination. Both the polarity of the photosignal and the typical maximum of the photocurrent suggest the hot carrier emission over the barrier to be responsible for the photocurrent formation at the higher forward bias, similarly as in a moderately doped p–n junction [3].

The decrease of the tunnel current when the junction is exposed to the CO_2 laser radiation can be explained by the free carrier heating. Let us assume that the degenerate electron and hole gases are heated by the laser radiation to the same temperature T_{e}. Then the photocurrent can be expressed as

$$I_{\mathrm{ph}} = A\frac{e[(U+U_T)T_0 - UT_{\mathrm{e}}]}{4kT_{\mathrm{e}}T_0}(E_C - E_V)^2. \quad (3)$$

As seen, the photocurrent is directly proportional to the change of the carrier temperature in warm electron region, when $T_{\mathrm{e}} - T_0 \ll T_0$.

Experimental study of the voltage U_{d} across the diode under the microwave radiation shows that U_{d} depends linearly on the microwave power in a wide intensity range (see Fig. 5). This is a characteristic feature of the emfs caused by free carrier heating [1]. The value of U_{d} at lower lattice temperature is higher than at room temperature. This fact can be explained by the higher value of the difference $T_{\mathrm{e}} - T_0$ at $T_0 = 80$ K compared to that at $T_0 = 300$ K. Since the value of carrier energy relaxation time increases with the decrease of the semiconductor lattice temperature [6], the value of $T_{\mathrm{e}} - T_0$ increases with decreasing T_0 at constant strength of the electric field.

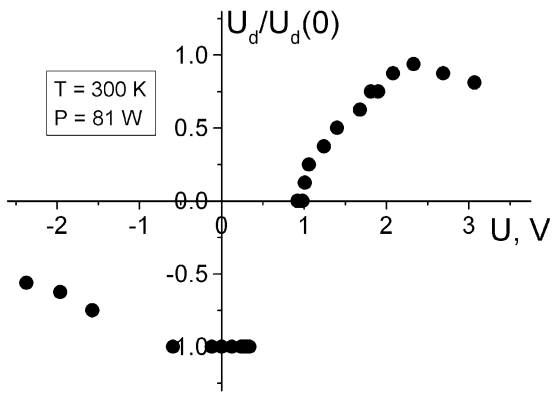


Fig. 7. The dependence of the photosignal (normalized to the zero-bias value) on applied bias voltage at room temperature. The diode is illuminated with the microwaves of 10 GHz frequency and 81 W incident power.

The dependences of U_{d} on the power at two different microwave frequencies are shown in Fig. 6. Apparently, the magnitude of U_{d} is almost independent of the frequency. This fact indicates that the main contribution to the measured voltage is related to the carrier heating by the electric field of the radiation, just as it was observed in the investigations of the hot carrier thermoelectric force arising across the n–n^+ junction [7].

It is worth to note that U_{d} strongly depends on the bias voltage applied to the diode (see Fig. 7). Several specific features of the dependence can be easily distinguished. First, the measured voltage monotonically varies with the bias voltage at reverse and low forward bias. Second, at higher values of the forward bias, U_d abruptly changes its polarity, what can be explained by the change of the nature of carrier flow across the $p{-}n$ junction. As already mentioned, in the case of the laser excitation at low values of forward bias the current flowing across the junction originates from the electron tunnelling through the barrier. Carrier heating causes the decrease of the magnitude of the tunnel current. As a result, the measured signal has negative polarity. When the forward bias is increased, the tunnel current diminishes, while the thermo-diffusive current rises. That is the reason why at forward bias the abrupt change of the U_d polarity takes place. Further increase of forward U causes the measured signal to reach its maximum value, and then to start decreasing. Such behaviour of U_d on the bias voltage is characteristic of all types of $p{-}n$ junctions, when the carriers are heated by external radiation [7].

4. Conclusions

Free carrier heating was experimentally observed for the first time in a degenerate semiconductor at room and liquid nitrogen temperatures. Nanosecond pulses of infrared radiation and microsecond pulses of microwave radiation were used as excitation sources. The magnitude of the response of the tunnel diode weakly depends on the frequency of the microwave radiation.

Acknowledgement

The investigated samples were fabricated at the Braun Center for Submicron Research of the Weizmann Institute of Sciences with kind assistance of Prof. M. Heiblum and Dr. H. Shtrikman under the support of the European Commission within the Large Scale Facility Programme (contract No. HPRI-CT-1999-00069).

References

[1] S. Ašmontas, J. Gradauskas, A. Sužiedėlis, E. Širmulis, and G. Valušis, Interaction of microwaves and infrared radiation with semiconductors: Study and applications, Lithuanian J. Phys. **40**(1–3), 15–25 (2000).

[2] S. Ašmontas and A. Sužiedėlis, Hot electron thermoelectricity, J. Thermoelectricity **1**, 5–26 (1997).

[3] S. Ašmontas, J. Gradauskas, D. Seliuta, A. Sužiedėlis, E. Širmulis, and G. Valušis, Application of hot-carrier thermo-electromotive force for measurement of pulsed microwave and infrared radiation, J. Thermoelectricity **4**, 15–28 (1998).

[4] S.Y. Liao, *Microwave Devices and Circuits*, 3rd edn. (Prentice-Hall, New York, 1990).

[5] K. Seeger, *Semiconductor Physics* (Springer-Verlag, Wien, 1973).

[6] A. Dargys and J. Kundrotas, *Handbook on Physical Properties of Ge, Si, GaAs and InP* (Science and Encyclopedia, Vilnius, 1994).

[7] S. Ašmontas, *Electrogradient Phenomena in Semiconductors* (Mokslas, Vilnius, 1984).

KARŠTIEJI KRŪVININKAI TUNELINIAME DIODE

S. Ašmontas [a,b], J. Gradauskas [a,c], J. Paukštė [b], V. Petkun [a], D. Seliuta [a],
A. Sužiedėlis [a,c], E. Širmulis [a], G. Valušis [a,c]

[a] *Puslaidininkių fizikos institutas, Vilnius, Lietuva*
[b] *Kauno technologijos universitetas, Panevėžio institutas, Panevėžys, Lietuva*
[c] *Vilniaus Gedimino technikos universitetas, Vilnius, Lietuva*

Santrauka

Pateikti pirmi laisvųjų krūvininkų kaitimo eksperimentinių tyrimų rezultatai, krūvininkus sužadinant tiek CO_2 lazerio spinduliuote, tiek ir 10 bei 35 GHz dažnio mikrobagomis. Tyrimams buvo naudojami tuneliniai GaAs $p{-}n$ diodai. Parodyta, kad krūvininkų kaitimas silpnina tamsinę tunelinę srovę, o esant pakankamai didelei išorinei tiesioginei įtampai, matuojamąjį signalą nulemia šiluminė-difuzinė srovė. Elektrovaros, atsirandančios paveikus diodą mikrobangomis, stiprumas yra tiesiogiai proporcingas spinduliuotės galiai ir didėja, žeminant puslaidininkio kristalinės gardelės temperatūrą, tuo tarpu jis beveik nepriklauso nuo mikrobangų dažnio.