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New GaAs infrared detector

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Abstract

We report our results of experimental study of photovoltage induced by pulsed CO_2 laser in GaAs p-n and l-h junctions. We demonstrate that photoemission of hot carriers across the potential barrier and the crystal lattice heating are the dominant mechanisms in the photovoltage formation. The obtained results show that hot-carrier effects in inhomogeneous GaAs can be used to detect very short infrared laser pulses.

Introduction

It is well known that the illumination of semiconductor with light the photon energy of which hν is larger than the forbidden energy gap E_g leads to electron-hole pair generation. In the case of p-n junction an ordinary photovoltaic effect occurs due to the separation of these electrons and holes by the internal electric field of the junction. On the other hand, when the photon energy is too small to generate the electron-hole pairs ($h\nu<E_g$), the photovoltage appears due to the thermo-electromotive force of the optically excited hot carriers [1-3]. In this case the photoresponse polarity is opposite to that of the photovoltaic effect. Since the hot-carrier energy relaxation time τ_{ε} is of the order of $10^{-11}\div10^{-12}$ s, the devices with l-h and p-n junction can be used as fast infrared (IR) detectors.

The behaviour of the hot-carrier photovoltage in Si, Ge and InSb p-n junctions has been under active investigation during the last decade [3-6]. It was established that the dependence of the detected signal on IR laser light intensity is linear in warm carrier region when the carrier heating is not so strong. At higher laser intensities the voltage sensitivity decreases due to the decrease of carrier energy relaxation time. As it is known [7], the electron energy relaxation time in GaAs at room temperature increases with the increasing electric field strength. Therefore, the voltage sensitivity of GaAs detector at high laser intensities may increase at room temperature. It implies that dynamic range of the detector can be extended.

The aim of this work is to investigate the photoelectric properties of GaAs p-n and l-h junctions under infrared laser radiation.

Experimental details

The ~300 μm thick substrates used for structure fabrication were: n-GaAs (tin-doped) with electron concentration $n=1.5\cdot10^{16}$ cm^{-3}, and p-GaAs (zinc-doped) with hole concentration $p=1.5\cdot10^{17}$ cm^{-3}. The investigated p-n junctions were formed by two different methods: by melting Sn+2%Zn alloy into n-substrate (t=500°C, fast cooling, H_2 atmosphere); as well as by growing up a ~2 μm thick p-type epitaxial layer on n-substrate by liquid-phase epitaxy (doped with germanium, t=800°C, 0.5°C/min. cooling, H_2 atmosphere) with subsequent mesas etching 0.4×0.4 mm^2 in square. The investigated $p-p^+$ and $n-n^+$ junctions were formed by Sn+2%Zn alloy and pure Sn melting into p- or n-substrate, respectively, under the same conditions as in the case of melted p-n junction. The diameter of melted contact was about 0.5 mm. All the created junctions were tested by measuring current-voltage (I-V) characteristics.

In the experiments the Q-switched CO_2 laser (wavelength 10.6 μm, repetition rate 40 Hz) with maximum power density 1 MW/cm^2 was used. The grown-up structures were illuminated from the epi-layer side, while the melted ones - from the substrate side.

Results and discussion

The operation of the detector is based on hot carriers emission over the potential barrier of GaAs p-n or l-h junction under IR radiation. Incident infrared radiation

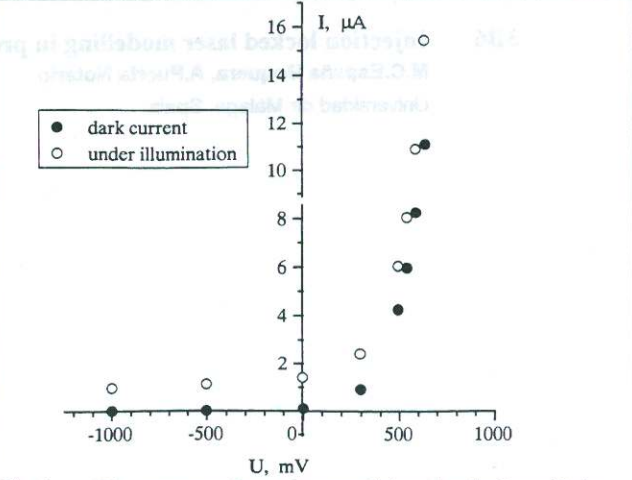

Fig. 1. The current-voltage characteristics of melted p-n-GaAs junction at T_o=300 K.

is absorbed by free carriers and the latters become hot carriers. If the hot carriers have energy greater than potential barrier height they can overcome the barrier. In the case of p-n junction, the barrier height can be easily varied by external bias voltage, that is at the same time we can alter the value of photocurrent. The I-V characteristics of melted p-n junction in the darkness and under the illumination are depicted in Fig. 1. It shows that the forward current under the CO_2 laser radiation increases, as it was in the case of germanium p-n junctions [3]. The direction of the photocurrent at reverse bias voltages indicates that there is no appreciable change of carrier concentration, in contrast to the case of usual solar cell.

The dependence of photocurrent I_{ph} on bias voltage applied to the p-n junction is shown in Fig. 2. It is seen that the abrupt increase of photocurrent takes place when the bias voltage "opens" the junction (U=0.4 V at room temperature of crystal lattice T_o=300 K, and U=0.7 V at T_o=80 K). The value of reverse photocurrent varies negligibly with voltage. The authors [3] explain that the negligible variation of photocurrent at reverse and low forward voltages is due to the recharging of self-capacitance of the junction when it is affected by a short laser pulse (displacement current).

The photocurrent increases with the increase of forward bias due to the decrease of barrier height. When the injection photocurrent through the barrier becomes larger than the capacitive current, the exponential increase of I_{ph} with U is observed. The saturation of photocurrent at high values of forward bias voltage is due to the negative feedback over the load resistance.

The dependencies of photocurrent (photovoltage on load resistance 1kΩ) upon incident laser light power of p-n junction with applied various bias voltages are presented in Fig. 3. The dependence of photoelectromotive force (photoemf) values (load resistance =∞) on incident laser intensity at T_o=80 K is depicted in the same figure. Like it was in the case of germanium p-n junctions [4], the detected signal depends on laser intensity closely to linear law at room temperature. Only at liquid nitrogen temperature some sublinearity may be observed. The reason of the latter will be discussed later.

In order to separate the contribution of hot electrons and hot holes into photovoltage of p-n junction we studied the photoemf appearing across n-n$^+$ and p-p$^+$ junctions, respectively. The dependence of photoemf arising on n-n$^+$ junction upon laser intensity is shown in Fig. 4. The magnitude of U_{emf} at liquid nitrogen temperature is larger than that at room temperature. This can be explained by the increase of electron energy relaxation time τ_ε with decreased lattice temperature [8]. It would be noted that U_{emf} linearly depends on laser intensity at room temperature, while at T_o=80 K this dependence is sub-linear. Such a behaviours are associated with the weak dependence of τ_ε on electric field strength at T_o=300 K [7], while at T_o=80 K the magnitude of τ_ε decreases rapidly with the increase of electron gas energy.

Similar results were obtained with p-p$^+$ junctions (Fig. 5). Still it should be noted that the magnitude of U_{emf} at liquid nitrogen temperature is slightly larger than that at T_o=80 K. Apparently, this fact can be explained by slight increase of hole energy relaxation time with the decrease of lattice temperature. Therefore, in the case of p-n junction the sublinear dependence of detected signal on laser intensity at T_o=80 K (Fig. 3) is caused by the decrease of electron τ_ε with the increase of electron gas energy.

The oscilloscope traces of photoemf U_{emf} on n-n$^+$ junctions are shown in Fig. 6. The analysis of the traces leads to the conclusion that U_{emf} consists of two components. The slow component U_T is strong at room temperature, while the fast component U_f is dominant at T_o=80 K. In order to estimate the amplitudes of these components the temporal analysis of photoemf was carried out. The temporal dependence of laser intensity can be properly approximated as:

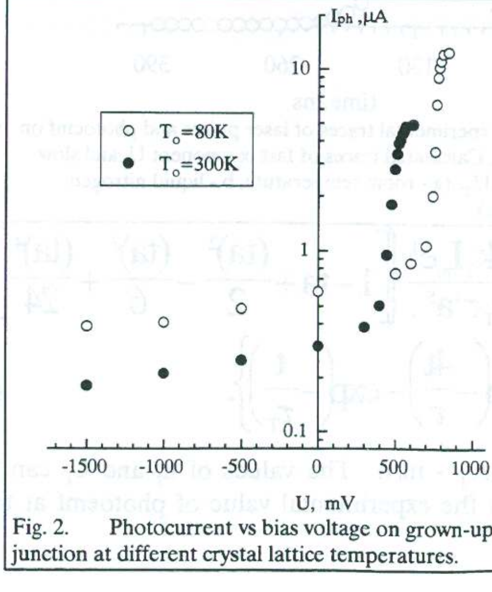

Fig. 2. Photocurrent vs bias voltage on grown-up mesa p-n junction at different crystal lattice temperatures.

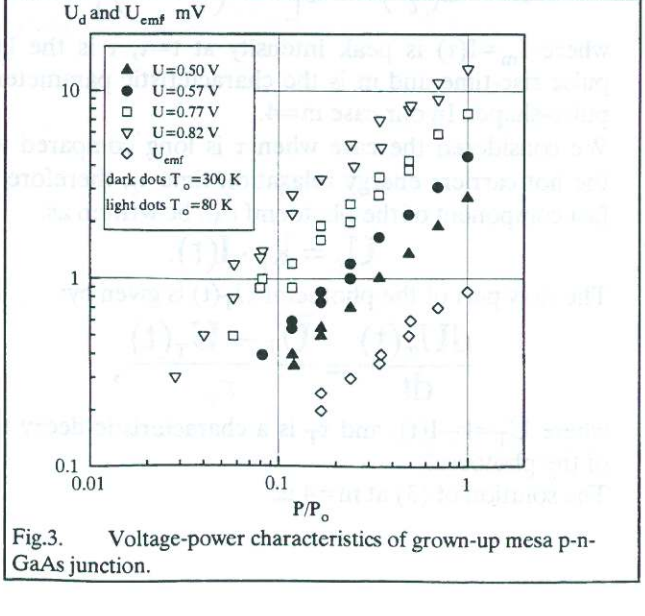

Fig.3. Voltage-power characteristics of grown-up mesa p-n-GaAs junction.

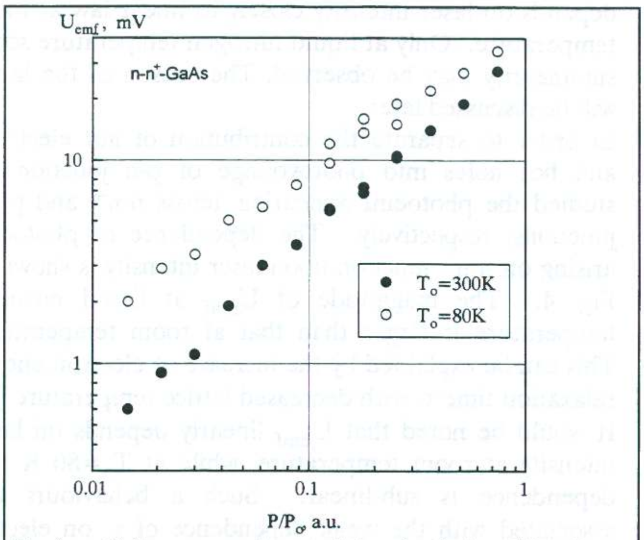

Fig. 4. Voltage-power characteristics of melted n-n$^+$ junction.

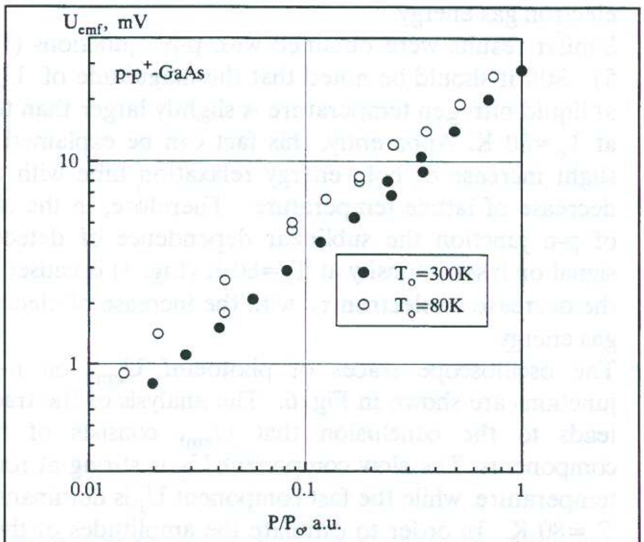

Fig. 5. Voltage-power characteristics of melted p-p$^+$ junction.

$$I(t) = I_m\left(\frac{t}{\tau}\right)^m \exp\left[-m\left(\frac{t}{\tau}-1\right)\right], \tag{1}$$

where $I_m=I(\tau)$ is peak intensity at $t=\tau$, τ is the laser pulse rise-time and m is the characteristic parameter of pulse-shape. In our case $m=4$.

We considered the case when τ is long compared with the hot carriers energy relaxation time τ_ε, therefore the fast component of the photoemf can be written as:

$$U_f = k_f \cdot I(t). \tag{2}$$

The slow part of the photoemf $U_T(t)$ is given by:

$$\frac{dU_T(t)}{dt} = \frac{\bar{U}_T - U_T(t)}{\tau_T}, \tag{3}$$

where $\bar{U}_T=k_T \cdot I(t)$, and τ_T is a characteristic decay time of the photoemf.

The solution of (3) at $m=4$ is:

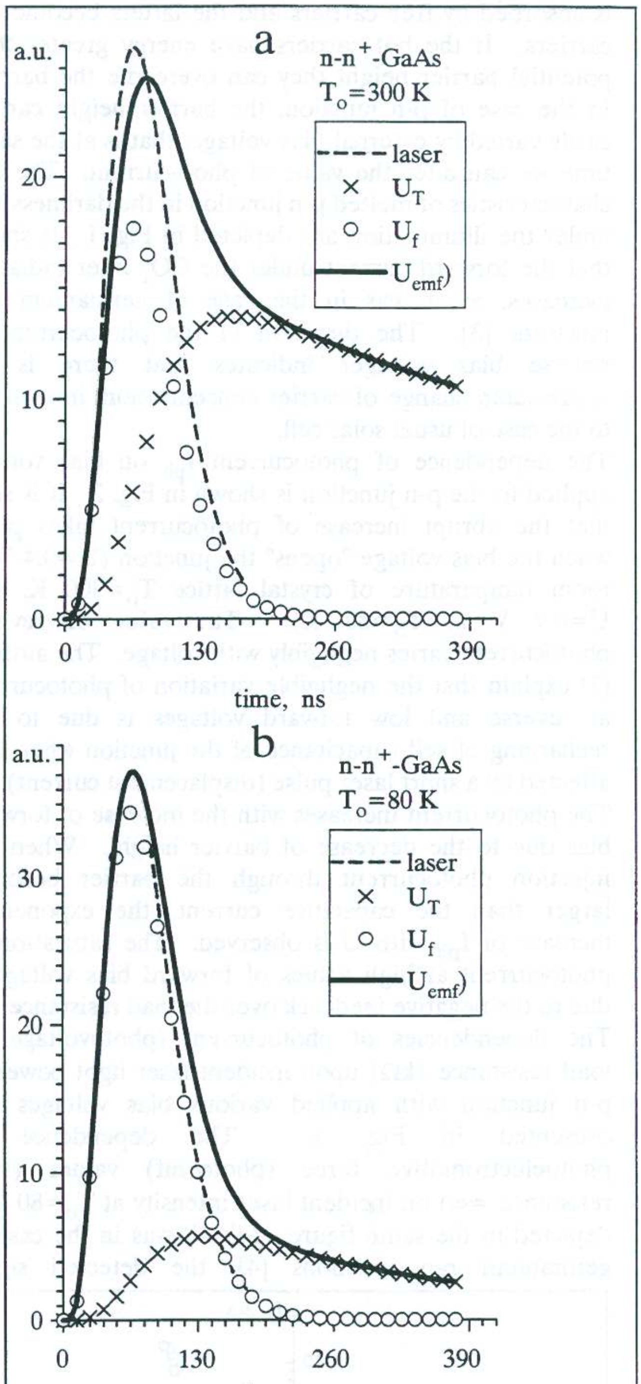

Fig. 6. Experimental traces of laser pulses and photoemf on n-n$^+$ junction. Calculated traces of fast component U_f and slow component U_T. (a - room temperatute, b - liquid nitrogen temperature).

$$U_T = \frac{24k_T I_m e^4}{\tau_T \tau^4 a^5}\left\{\left[1-ta+\frac{(ta)^2}{2}-\frac{(ta)^3}{6}+\frac{(ta)^4}{24}\right]\times \exp\left(-\frac{4t}{\tau}\right)-\exp\left(-\frac{t}{\tau_T}\right)\right\}. \tag{4}$$

Here $a=1/\tau_T - m/\tau$. The values of k_f and k_T can be found from the experimental value of photoemf at $t=\tau$

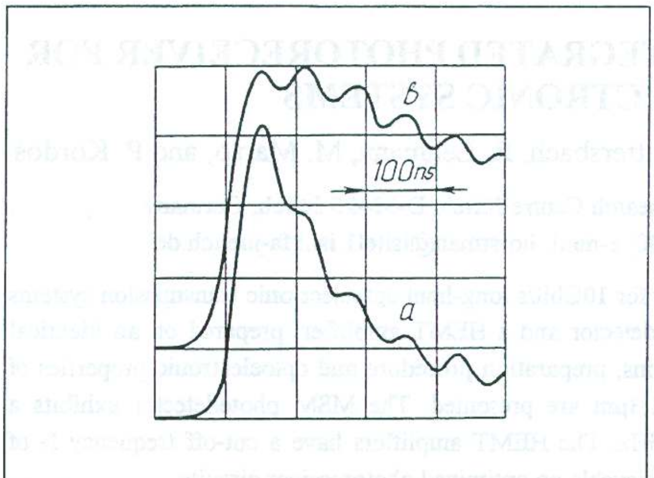

Fig. 7. Laser pulse shaped by transverse mode beating (a) and photoemf on n-n$^+$ junction at room temperature (b).

and $t=t_m$, respectively. The t_m is defined by $dU_T/dt=0$ at the moment when $t=t_m$.

As illustrated in both Fig. 6a and Fig. 6b the calculated curves agree with experimental traces. Thus the above approximation let us separate and determine both the hot-carrier effect and the thermoelectric effect caused by crystal lattice heating. The results of calculations (Fig. 6) clearly show that the contribution of the fast component into U_{emf} is signifficant even at room temperature.

In order to elucidate experimentally the fast component of the photoemf the pulsed CO_2 laser with transverse mode beating was used [9]. The laser provided a possibility to obtain pulses with rise time of about 20 ns. At room temperature the photoemf trace shows the fast pulsetrain (Fig. 7b) which agrees with the laser pulse trace measured by photon-drag detector (Fig. 7a).

Conclusions

On the basis of the findings above it is reasonable to conclude that the free carrier heating by nanosecond CO_2 laser pulses is responsible for the fast photovoltage formation in GaAs p-n and l-h junctions. It let us separate and determine both the hot-carrier and the lattice heating effects. Moreover, the hot-carrier photovoltage measurements is a promising technique to determine the carrier temperature and the energy relaxation time in GaAs. The obtained results show that inhomogeneous GaAs structures can be used for fabrication of fast infrared detectors.

References

[1] I. J. Marmur, J. A. Oksman, and A. A. Semenov, "The hot carrier current through p-n junction," *Phys. Tekh. Poluprovodn.*, vol. 8, no. 11, pp. 2216-2217, 1974 (in russian).

[2] M. Umeno, Y. Sugito, T. Jimbo, H. Hattori, and Y. Amemiya, "Hot photo-carrier and hot electron effects in p-n junctions," *Solid. St. Electron.*, vol. 21, no. 1, pp. 191-195, 1978.

[3] S. Ašmontas, E. Širmulis, and S. Stonys, "Investigation of the photovoltage across germanium p-n junction under pulsed CO_2 laser irradiation," *Lietuvos fizikos rinkinys*," vol. 24, no. 3, pp. 76-82, 1984 (in russian).

[4] S. Ašmontas, E. Maldutis, and E. Širmulis, "CO_2 laser radiation detection by carrier heating in inhomogeneous semiconductors," *Int. J. of Optoelectronics*, vol. 3, no. 3, pp. 263-266, 1988.

[5] S. Ašmontas, J. Gradauskas, and E. Širmulis, "Hot carrier silicon phototransistor," *Infrared and Optoelectronic Materials and Devices, Proc. SPIE*, vol. 1512, pp. 131-134, 1991.

[6] S. Ašmontas, J. Gradauskas, and E. Širmulis, "CO_2-laser induced photoeffects in inhomogeneous InSb," *Digest of 5th European Quantum Electron. Conf., Amsterdam*, pp. 154-155, 1994.

[7] K. Ahida, M. Inoue, J. Shirafuji, and Y. Inuishi, "Energy ralaxation effect of hot electrons in GaAs," *J. Phys. Soc. Jap.*, vol. 37, no. 2, pp. 408-414, 1974.

[8] S. Ašmontas and A. Sužiedėlis, "Electrical properties of small area GaAs n-n$^+$ junction," *Lithanian Journal of Physics*, vol. 33, no. 1, pp. 45-51, 1993.

[9] A. Merkys, S. Stonys, and E. Širmulis, "A simple current pulsed low-pressure CO_2 laser with passive Q-switching," *Optical and Quantum Electron.*, vol. 20, no. 2, pp. 373-376, 1988.