GAAS® 97 • 5th European Gallium Arsenide and related III-V compounds Applications Symposium
Bologna, Italy - September 3rd-5th, 1997

GaAs/AlGaAs heterojunction: a promising detector for infrared radiation

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Abstract

We report our results on experimental study of photovoltage, induced by pulsed CO_2 laser in GaAs/AlGaAs heterojunctions. We show that photoemission of hot carriers across the potential barrier is the dominant mechanism in formation of the photovoltage. The analysis of the current-voltage characteristic reveals that the photocurrent has maximum at bias voltage related to the potential barrier height of p-n heterojunction. Moreover, we demonstrate that the use of heterojunction has an advantage over homojunction in the infrared detection.

Introduction

When a non-uniform semiconductor structure is illuminated with light photon energy of which is smaller than the forbidden energy gap, electromotive force (emf) appears due to diffusion of the optically excited (so called 'heated') free carriers [1,2]. In case of p-n junction polarity of the photovoltage is opposite to that of the ordinary photovoltaic effect. Since hot-carrier energy relaxation time is of the order of $10^{-11} \div 10^{-12}$ s, devices based on free carrier heating can be used as fast infrared (IR) detectors. In contrast to narrow-gap semiconductor detectors, operating at low temperatures, these devices may be successfully used at conventional temperatures, that is, cryogenic cooling is not necessary.

The behaviour of the hot-carrier photovoltage in Si, Ge, InSb and GaAs p-n and l-h junctions have been under active investigation during the last years [3-7]. It was established that the detected photoresponse linearly depends on the laser intensity up to the 1MW/cm^2 values. The use of p-n junction has advantage over the l-h junction, since the magnitude of the photoresponse can be varied by external voltage. Moreover, the analysis of the photoresponse pulse shape showed [6,7] that it consists of two components: the fast one due to the free carrier heating, and the slow one connected with the crystal lattice heating by IR light. At room temperature the total photosignal falls with time constant of several microseconds due to the significant contribution of the slow component. The present communication deals with the peculiarities of the photoresponse formation in GaAs/AlGaAs p^+-n and n^+-n heterojunctions in comparison with that of GaAs homojunctions under CO_2 laser radiation.

Experimental details

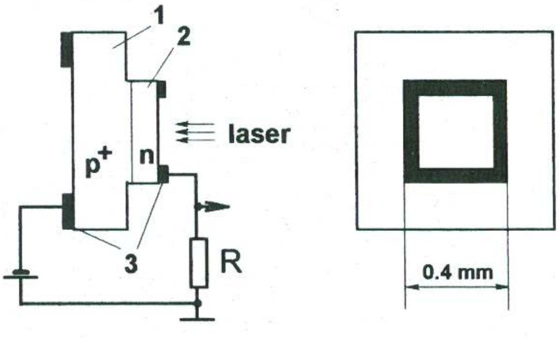

Fig. 1. Schematic view of grown-up mesa structure and measurement circuit:1- substrate, 2- epilayer, 3-ohmic contacts, R- load resistance.

The investigated structures were formed by LPE-growing of thin (3÷5 μm) $Al_{0.1}Ga_{0.9}As$ (or GaAs) epitaxial layers on GaAs substrates, with consequent etching of mesas 0.4×0.4 mm^2 in square (see Fig. 1). The electron or hole concentrations in ~300 μm thick substrates were $p^+=7\cdot10^{17}$ cm^{-3} (zinc-doped) or $n^+\approx10^{18}$ cm^{-3} (tin-doped), respectively. The electron concentration in the epitaxial layer was $n=10^{16}$ cm^{-3}. 10 percent of aluminium in AlGaAs layer were chosen so that the energy band discontinuities at the interface does not exceed the photon energy . Quality of p-n junctions was tested by measuring current-voltage (I-V) characteristics. For excitation Q-switched CO_2 laser was used (operation wavelength 10.6 μm, pulse duration 150 ns, repetition rate 40 Hz, maximum power density about 2 MW/cm^2).

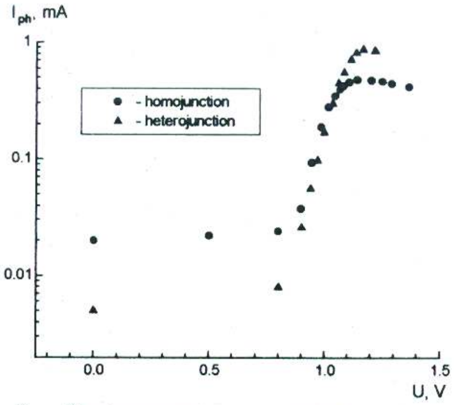

Fig. 2. Photocurrent across p^+-n GaAs/AlGaAs and GaAs junctions versus applied voltage.

Results and discussion

When the p^+-n GaAs/AlGaAs heterojunction is illuminated with CO_2 laser light, the photoemf appears with sign opposite to that of the ordinary photovoltaic effect. Photocurrent of the hot carriers (photovoltage on load resistance, see Fig. 1) is measured. Its magnitude strongly depends on the bias voltage applied to the junction (see Fig. 2). The shape of the photocurrent-voltage characteristic of the heterojunction is close to that of GaAs p^+-n homojunction, depicted in the same picture. However, there are some specific differences which will be noted below. (It is worth noting, that the doping levels of n and p^+ regions of the homojunction are the same as those of the heterojunction, and, in addition, the geometrical parameters of the samples also are the same. Moreover, the intensity of the CO_2 laser radiation is the same in both cases.) Three regions of this characteristic may be singled out: i- weak dependence on reverse voltage; ii- abrupt growth at definite value of the bias voltage; and iii- maximum value. Let us analyse them separately.

As it was mentioned earlier [6,7], the negligible variation of the photocurrent across p-n junction at reverse and low forward voltages is due to the recharging of self-capacitance of the junction affected by a short IR laser pulse (displacement current or capacitive current). The height of the potential barrier of the junction is high enough, and the free carriers heated by IR light cannot overcome it. At first sight, no photocurrent should flow. But since the barrier is not right, i.e. its height changes with distance, the hot carriers diffuse towards the metallurgical boundary of the junction. In other words, the width of the depleted region decreases. If the p-n junction is considered as a plane capacitor, its capacitance may be expressed just as:

$$C = \frac{Q}{V} \, , \tag{1}$$

where Q and $V = V_k + U$ are the charge and the potential difference of the capacitor (U- the external voltage). If the junction is doped strongly asymmetrically (as it is in our case), its capacitance per unit square can be expressed as [8]:

$$C = \left(\frac{2e\varepsilon\varepsilon_o n}{V_k} \right)^{1/2} \frac{V_k}{V_k + U_{ph}} \, . \tag{2}$$

Here e denotes the elementary charge, n stands for the carrier concentration of lightly doped region of the junction, V_k is the potential barrier height, and U_{ph} stands for the photoemf arising on the junction under illumination; ε and ε_o are the permittivities of the material and vacuum, respectively. If the load resistance R (see Fig. 1) is much lower than that of the junction, then $V \approx V_k$ and the short-circuit photocurrent is:

$$I_{ph} = \frac{dQ}{dt} = V_k \frac{dC}{dt} = -\frac{CV_k}{V_k + U_{ph}} \cdot \frac{dU_{ph}}{dt} \, . \tag{3}$$

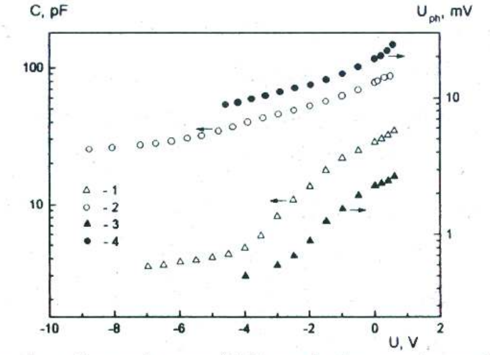

Fig. 3. Capacitance (1,2) and photovoltage (3,4) versus bias voltage applied to p^+-n GaAs/AlGaAs (1,3) and GaAs (2,4) junctions.

It is seen from Eq. 3 that the photocurrent of 'closed' p-n junction is proportional to the capacitance of the junction. The photovoltage detected on the load resistance as well as the capacitance of both heterojunction and homojunction are presented in Fig. 3. The value of this photovoltage depends on reverse and low forward bias voltage according to the same law as the measured value of the capacitance of both junctions does. It clearly proves our consideration above: when the p-n junction is 'closed' (the barrier height is too high for the hot carriers to overcome it), the capacitive current flows under IR illumination. Since the measured capacitance of the heterojunction is lower than that of the homojunction (Fig. 3), therefore, the value of the photocurrent is lower as well, while the intensity of radiation is the same in both cases. Moreover, its to be emphasized, that according to Eq. 3 I_{ph} is proportional to the speed of the photoemf, i.e. to the inverse duration of the U_{ph}. It means that the mentioned capacitive effect may be valuable in the detection of short IR laser pulses: the shorter laser pulse, the higher value of capacitive photocurrent is detected.

When the junction is 'opened', that is when the diffusion current of hot carriers over the potential barrier exceeds the capacitive current, the exponential increase of the photocurrent is observed (see Fig. 2). It agrees with theoretical predictions [7] as well as with experimental results obtained on other semiconducting materials [2,4,9]. It is clearly seen (Fig. 2) that the photocurrent across the heterojunction increases exponentially over the wider range of its values, in comparison to that of the homojunction, what enables one to determine precisely the slope of this exponential dependence. Therefore, taking into account the ideality factor of the current-voltage characteristic and assuming that just only the hot holes are responsible for the photocurrent flow (since the junction is asymmetrically doped), we have evaluated the temperature of hot-hole-plasma: T_p=1.1 T_o at crystal lattice temperature T_o=300K. These numbers seem to be reasonable, since the temperature of hot-carrier-plasma in case of germanium illuminated with CO_2 laser light was of the same order of magnitude [9].

As it was mentioned [7], photocurrent across the p-n homojunction increases exponentially and reaches its maximum value at applied voltage value U_m closely related to the potential barrier height:

$$U_m = V_k - \frac{kT_oT_p}{e(T_p - T_o)} \ln \frac{T_p j_{pso}}{T_o j_{ps}}. \tag{4}$$

where j_{so} and j_s are the saturation currents of the I-V characteristic in the dark and under illumination, respectively. Eq. 4 shows, that the higher is potential barrier height, the higher bias voltage should be applied to reach the maximum value of the photocurrent. The normalized to unity upper parts of the photocurrent-voltage characteristics of both p^+-n GaAs and GaAs/AlGaAs junctions are depicted in Fig. 4. It is seen that the photocurrent across the homojunction reaches its maximum value at lower bias voltage than does that of the heterojunction. This difference is more pronounced at the exponential rise of the photocurrent: that of the heterojunction is shifted to the higher voltages. The reason of this fact may be explained according to Eq. 4: since the heights of the barriers due to the doping gradient may be considered equal in both junctions, nevertheless, the

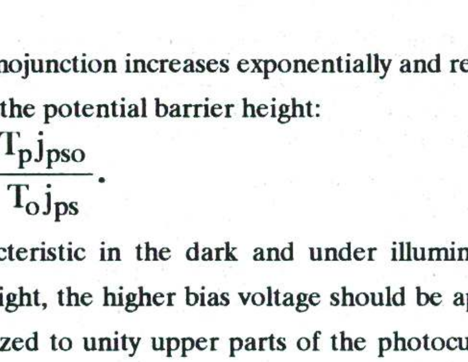

Fig. 4. Normalized to unity photocurrent-voltage characteristics from Fig. 2 (upper parts).

heterojunction has additional barrier due to the difference in the forbidden energy gap. Consequently, additional bias voltage should be applied to make the photocurrent reach its maximum value. Calculations provide discontinuities of conduction and valence bands in the heterojunction equal 80 meV and 45 meV, respectively. The experimental results (Fig. 4) show that I_{ph}-V characteristic of the heterojunction is shifted by about 60 mV with respect to that of the homojunction. Good agreement between calculated and experimental results proves the above considerations. As concerns the value of the photocurrent, it is worth noting, that the maximum value of I_{ph} across the heterojunction is higher than that across the homojunction.

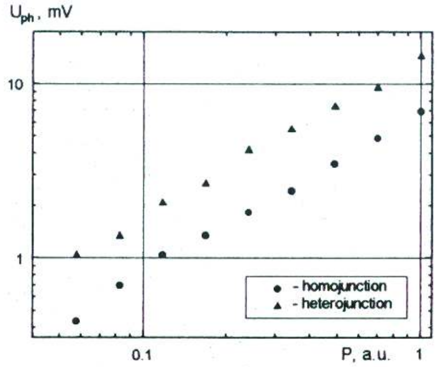

Fig. 5. Photoemfs on n^+-n GaAs/AlGaAs and GaAs junctions versus laser intensity.

The dependencies of photoemf on n^+-n both heterojunction and homojunction are presented in Fig. 5. The linear dependence of the detected signal on the CO_2 laser light intensity (in the measured intensity range), as well as its polarity confirm the fact that the photoemf is caused by the free carrier heating. The sensitivity of the heterojunction is more than two times higher than that of the homojunction. The reason of this may be the existence of potential barrier due to the discontinuity of the conduction band in the case of heterojunction.

Conclusions

On the basis of these findings, it seems reasonable to conclude that the free carrier heating by nanosecond CO_2 laser pulses is responsible for the photovoltage formation in GaAs/AlGaAs p-n junction, just like it was in the case of GaAs homojunction. Nevertheless, application of the heterojunction due to its higher sensitivity seems to be more favourable in the infrared detection at room temperature.

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