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Photovoltage formation across GaAs p–n junction under illumination of intense laser radiation

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Abstract Peculiarities of photovoltaic effect in GaAs p–n junction under laser excitation at 10.6 and 1.06 μm wavelengths has been investigated experimentally. When photon energy is far less than the forbidden energy gap, the photovoltage is found to be caused by hot carrier electromotive force. When the junction is illuminated with intense Nd:YAG laser radiation, the photovoltage is recognized to consist of two components, $U = U_f + U_{ph}$. The first one U_f is the fast component having polarity of thermoelectromotive force of hot carriers. The second one U_{ph} is the slow component of opposite polarity, and it is caused by electron–hole pair generation due to two-photon absorption of laser radiation.

Keywords p–n junction · GaAs · Hot carrier photovoltage · Two-photon absorption · Laser radiation

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1 Introduction

Photovoltaic effect is observed when nonuniform semiconductor is illuminated with laser radiation. It is known (Ašmontas et al. 2001) that two mechanisms are dominant in photovoltage formation. When photon energy is larger than the forbidden energy gap E_g, the illumination leads to electron–hole pair generation, and an ordinary photovoltage arises across p–n junction due to separation of electrons and holes in the internal electric field of the junction. If photon energy is lower than the forbidden energy gap, the intraband free carrier absorption leads to carrier heating. As a result, hot carrier photovoltage is induced. For the first time it was observed across germanium p–n junction under CO_2 laser radiation (Marmur et al. 1974). Later, hot carrier photoelectromotive force was investigated in Si (Andrianov et al. 1980), in Ge (Umeno et al. 1978), in InSb (Ašmontas et al. 1994), in GaAs (Ašmontas et al. 2001) p–n junctions.

Internal photoemission of hot carriers was observed across hetero- (or homo-) junctions at low temperatures (Coon et al. 1989; Perera et al. 1995, 1997, 2001). Photovoltaic infrared detectors based on internal photoemission of hot carriers have significant advantages over photoconductive detectors due to zero-biased operation requiring low power and having reduced low frequency noise (Pitigala et al. 2012). Since the hot carrier energy relaxation time is of the order of 10^{-10}–10^{-12} s, the photovoltaic detector can be used to detect short infrared light pulses (Ašmontas et al. 2003). It is noteworthy that the photovoltage is a linear function of laser intensity at low excitation levels. At high excitation level multiphoton absorption effects can be observed (Gradauskas et al. 2011). Carrier heating and electron–hole generation may act simultaneously within the junction thus strongly impacting on responsivity and speed of operation of the device.

In this paper we report a photovoltage across GaAs p–n junction under pulsed radiation of CO_2 and Nd:YAG lasers. The influence of carrier heating and electron–hole pair generation on the magnitude of the measured photovoltage is considered.

2 Experimental details

The investigated GaAs p–n junctions were formed by liquid phase epitaxy-grown p-type 5 μm thick layers with hole density 5×10^{17} cm^{-3} on n-type substrate with electron density 3.5×10^{17} cm^{-3}. To create the ohmic contact, thin p^+-layer with hole density 2×10^{18} cm^{-3} was grown upon the layer. AuGeNi alloy was deposited by thermal evaporation, and metallic contacts were fabricated by the lift-off technique. The p–n junction was illuminated from the epitaxial layer side through the square window etched

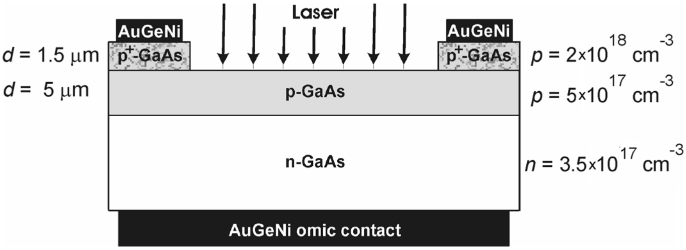


Fig. 1 Schematic sample structure (not to scale)

in p$^+$-layer (Fig. 1). In the experiments, the Nd:YAG laser with wavelength 1.06 µm and pulse duration 25 ns as well as the Q-switched CO$_2$ laser with wavelength 10.6 µm were used. The laser beams were focused on the sample surface to increase the excitation intensity, thus reaching maximum pulse intensity around I_0= 1 MW/cm^2. Temporal behavior of the photovoltage and laser pulse in nanosecond time scale was recorded by digital storage oscilloscope Instek GDS-2202. All the measurements were carried out at room temperature.

3 Results and discussion

Photovoltage arises when the GaAs p–n junction is illuminated with CO$_2$ laser radiation. The polarity of it corresponds with the polarity of thermoelectromotive force of hot carriers. The dependence of the photocurrent j_f on bias voltage applied on the p–n junction is shown in Fig. 2. It is seen that the value of photocurrent varies negligibly with reverse bias. Earlier it was shown (Ašmontas et al. 2005) that the photocurrent at reverse and low forward bias is caused by the recharging of self-capacitance of the junction affected by a short laser pulse. The potential barrier height of the junction is high enough, and not all free carriers photoexcited by the CO$_2$ laser radiation can overcome it. The hot carrier photocurrent increases with higher forward bias values due to decreased barrier height. When the injection photocurrent through the barrier becomes larger than the capacitive current, exponential growth of j_f with bias is observed (see Fig. 2).

The photocurrent reaches its maximum value at bias voltage U_m, and at higher voltages j_f starts to decrease. The experimental dependence of j_f on applied voltage can be explained considering hot carrier flow through p–n junction.

Calculation of current–voltage characteristic of a p–n junction under electron temperature approximation leads to expression of total current flowing across the junction as

$$j=\frac{eD_n n_p}{L_n}\left\{\exp\left[\frac{eU}{kT_n}+\frac{eV_k}{kT_0}\left(1-\frac{T_0}{T_n}\right)\right]-1\right\}+\frac{eD_p p_n}{L_p}\left\{\exp\left[\frac{eU}{kT_p}+\frac{eV_k}{kT_0}\left(1-\frac{T_0}{T_p}\right)\right]-1\right\}, \tag{1}$$

where e is the elementary electron charge, $D_{n,p}$ and $L_{n,p}$ are the diffusion coefficient and diffusion length for electrons and holes, respectively, n_p and p_n are the electron and hole densities in p- and n-regions, respectively, U is bias voltage, k is the Boltzmann constant,

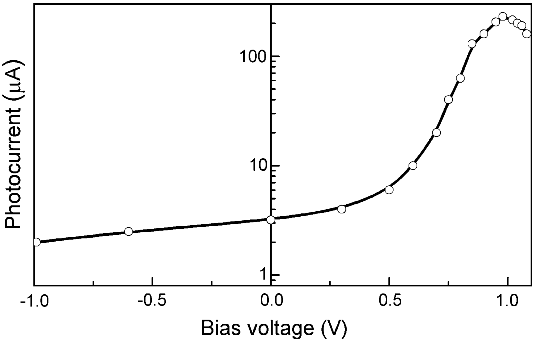


Fig. 2 Photocurrent across GaAs p–n junction illuminated with CO$_2$ laser light versus bias voltage

T_n and T_p are the temperatures of electron and hole gases, respectively, eV_k is the potential barrier height of p–n junction, T_0 is the lattice temperature.

It is established (Ašmontas et al. 2001) that the temperatures of hot electrons and hot holes are nearly equal, $T_n \approx T_p$, in GaAs under the excitation of CO_2 laser radiation. Taking into account this fact we obtain expression for the photocurrent

$$j_f = j - j_0 = j_s\left\{\exp\left[\frac{eU}{kT_n} + \frac{eV_k}{kT_0}\left(1 - \frac{T_0}{T_n}\right)\right] - 1\right\} - j_{s0}\left(\exp\frac{eU}{kT_0} - 1\right), \tag{2}$$

where j_{s0} and j_s are the reverse current densities in the dark and under the illumination, respectively. Differentiation of Eq. (2) with respect to U gives

$$\frac{dj_f}{dU} = \frac{ej_s}{kT_n}\exp\frac{eU}{kT_0}\left\{\exp\left[\frac{e(V_k - U)}{kT_0}\left(1 - \frac{T_0}{T_n}\right)\right] - \frac{T_n j_{s0}}{T_0 j_s}\right\}. \tag{3}$$

Equation (3) shows that the derivative dj_f/dU changes its sign at bias voltage

$$U_m = V_k - \frac{kT_n T_0}{e(T_n - T_0)}\ln\frac{T_n j_{s0}}{T_0 j_s}. \tag{4}$$

It means that at $U > U_m$ the photocurrent starts to decrease with U, as it is observed in the experiment (see Fig. 2).

The dependencies of photovoltage U_f on the intensity I of CO_2 laser radiation at different bias values are depicted in Fig. 3. It is seen that U_f is a linear function of I in all the used laser power range. It is worth noting that the photovoltage has only one component in case when the photon energy is far less than the forbidden energy gap.

Another situation occurs when the photon energy becomes comparable to the forbidden energy gap. Figure 4 presents temporal profiles of the photovoltage U across the GaAs p–n junction induced by Nd:YAG laser pulses. As can be seen, U has only one component U_f at low excitation level. The polarity of U_f corresponds with the polarity of thermoelectromotive force of hot carriers. The photovoltage shape changes with increasing laser power. At higher excitation level it consists of two components:

$$U = U_f + U_{ph}. \tag{5}$$

The slow component U_{ph} has polarity opposite to that of U_f thus indicating the former to be caused by electron–hole pair generation during the illumination. Investigation of U_{ph} dependence on applied bias voltage shows that U_{ph} decreases rapidly with forward bias and increases with the reverse bias. Similar behavior of the generation-induced U_{ph} on the

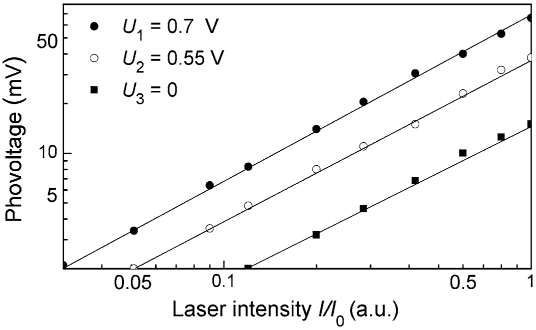


Fig. 3 The dependence of hot carrier induced photovoltage on intensity of CO_2 laser radiation

Fig. 4 Photovoltage traces in p–n GaAs junction for different laser power P at $\lambda = 1.064$ µm

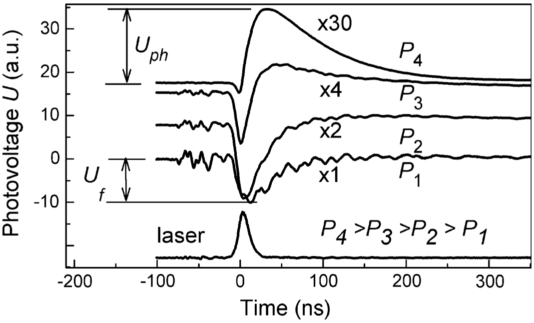
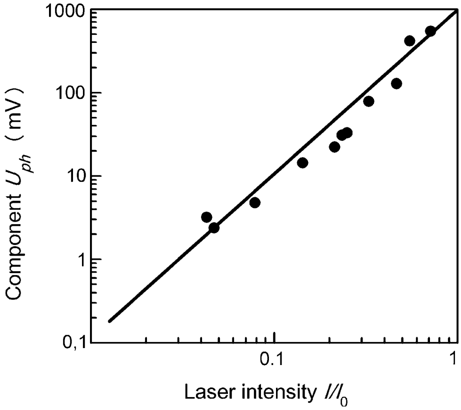


Fig. 5 The carrier generation-based component of the photovoltage across GaAs p–n junction versus laser intensity



applied bias voltage was observed earlier in narrow-gap semiconductor p–n junction under the action of intense pulses of CO_2 laser radiation (Gradauskas et al. 2011).

When the excitation level is increased, the magnitude of U_{ph} increases following the square law (see Fig. 5). This fact indicates that the electron–hole pair generation is determined by two-photon absorption since the single photon energy of the Nd:YAG laser is lower than the forbidden energy gap of GaAs.

At low excitation levels the fast component U_f linearly depends on laser intensity (see Fig. 6). But at higher intensities of laser radiation U_{ph} becomes more dominating (see Fig. 4).

Temporal analysis of the photovoltage was carried out to separately estimate the magnitudes of U_f and U_{ph}. The time-dependence of Nd:YAG laser pulse intensity can be properly approximated as

$$I(t) = I_m\left(\frac{t}{\tau}\right)^4 \exp\left[4\left(1-\frac{t}{\tau}\right)\right], \tag{6}$$

where I_m is the peak intensity at $t = \tau$, $I_m = I(\tau)$, and τ is the laser rise-time. Since τ is much longer than the hot carrier energy relaxation time, the fast component of the photovoltage can be expressed as

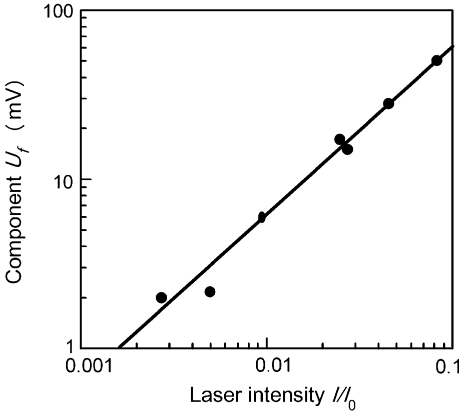


Fig. 6 The hot carrier induced component of the photovoltage versus laser intensity

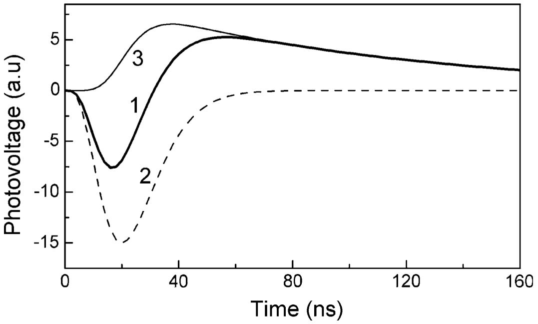


Fig. 7 Experimental trace of photovoltage (curve *1*) and calculated fast component U_f (*2*) and slow component U_{ph} (*3*)

$$U_f = K_f \cdot I(t). \tag{7}$$

The slow component of the photovoltage U_{ph} (t) is found from

$$\frac{dU_{ph}(t)}{dt} = \frac{\bar{U}_{ph} - U_{ph}(t)}{\tau_{ph}}, \tag{8}$$

where $\bar{U}_{ph} = K_{ph} \cdot I^2(t)$, and τ_{ph} is the characteristic decay time of U_{ph}. The solution of (8) gives

$$U_{ph}(t) = \frac{8!e^8 K_{ph} I_m^2 \tau}{a^9 \tau_{ph}} \left\{ \exp\left(-\frac{t}{\tau_{ph}}\right) - \left[1 + \sum_{n=1}^{8} \frac{(bt)^n}{n!}\right] \exp\left(-\frac{8t}{\tau}\right) \right\}. \tag{9}$$

Here $a = (8\tau_{ph} - \tau)/\tau_{ph}$ and $b = a/\tau$. The values of coefficients K_f and K_{ph} can be found from experimental magnitude of the photovoltage at $t = \tau$ and $t = t_m$, respectively. The t_m is defined by $dU_{ph}/dt = 0$ at the moment when $t = t_m$.

The calculated curves are depicted in Fig. 7. It is seen that both agree with experimental temporal trace. Thus the above presented approximation let us separate and determine both the hot carrier effect and electron–hole pair generation-based components of the photovoltage induced across the p–n junction.

4 Conclusions

Formation of photovoltage across p–n junction illuminated with nanosecond pulses of intense laser radiation was investigated. The laser radiation of 10.6 μm wavelength leads to free carrier heating and formation of thermoelectromotive force of hot carriers; it is directly proportional to the laser intensity. The laser radiation of 1.06 μm leads to formation of two components. The fast one is caused by the laser-induced free carrier heating, and the slow one is an ordinary photovoltage arising across p–n junction due to separation of radiation-generated electrons and holes within internal electric field of the junction. The slow component of the photovoltage U_{ph} was found to increase with laser intensity according to the square law. At low excitation levels of the 1.06 μm wavelength the photovoltage is mainly stipulated by the thermoelectromotive force of hot carriers, and at high intensities the photovoltage is mainly due to generation of electron–hole pairs. The reported results can find application in the development of high power optoelectronic devices, e.g., solar cell concentrator systems.

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