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Impact of proton implantation parameters on the photoconductivity of photorefractive multiple quantum wells

Błażej Jabłoński*[1] Agnieszka Branecka[1], Eliza Miśkiewicz[1], Andrzej Ziółkowski[1], Ewa Weinert-Rączka[1]

[1]West Pomeranian University of Technology in Szczecin, Piastów 17, 70-310 Szczecin,

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Abstract—Semi-insulating GaAs/AlGaAs multiple quantum wells are photorefractive materials with high sensitivity and short response time. Semi-insulation of these structures is commonly obtained by proton implantation. We present the measurements of photoconductivity in the samples with different proton doses. The results were compared to the theoretically predicted relationship between photoconductivity and the donor to acceptor concentration ratio. This allows to estimate the impact of proton dose on deep donor concentration.

The photorefractive effect is an optically induced change in the refractive index due to non-homogeneous illumination [1-2]. The material in which the photorefractive effect can be obtained should exhibit sufficiently high dark resistivity, photoconductivity and electro-optic effect. In the case of photorefractive semiconductors resistivity is usually increased by proton irradiation, which creates defects in the structures. It is essential to estimate the influence of proton implantation on various properties of the structure. This study presents the current-voltage characteristics of uniformly illuminated photorefractive multiple quantum wells (PR-MQW) that were treated by different doses of protons. The experimental results have been compared to a theoretically predicted dependence of current density on electric field for various defect concentrations.

The commonly used model of a photorefractive phenomenon in quantum wells assumes that two types of 'defect' levels occur in the energy gap: deep donors with concentration N_D and shallow acceptors with concentration N_A. The presence of shallow levels is the reason why the structure before implantation had relatively strong dark conductivity. Proton implantation creates deep levels that compensate for shallow dopants existing in the material and act as traps in photorefractive effect.

When an electric field with intensity above the critical value $E_A \approx 3\ \mathrm{kV/cm}$ is applied to a PR-MQW structure, nonlinear phenomena due to changes in electron mobility begin to take place. These phenomena turn out to be crucial from both cognitive and practical perspectives, affecting photorefractive gain during wave mixing [3-5] and non-linear propagation of light beams in semiconductors [6]. Changes in the mobility result from increasing energy of electrons, which is described as the increase of electron temperature that gets much higher than the temperature of lattice $T_e \gg T_L$. Electron temperature can be expressed by the relation [7]:

$$T_e(E) = T_L + \frac{2q\tau_r\mu_e(E)}{3k_B}E \tag{1}$$

where $\mu_e(E)$ is the mobility of electrons dependent on electric field intensity, τ_r is the mean energy relaxation time, q is the elementary electric charge, and k_B is the Boltzmann constant.

In the conductivity band of semiconductors such as GaAs, apart from the central valley there are side valleys characterized by lower mobility. When the intensity of an electric field applied to the structure exceeds the value E_A, a part of the electrons is transferred from the central valley to side valleys. This is usually described by a 'two valleys' model, in which electron mobility is expressed as the weighted average:

$$\mu(E) = \mu_{el}f(E) + \mu_{eu}[1 - f(E)] \tag{2}$$

where μ_{el} and μ_{eu} are electron mobilities in, respectively, central valley and side valley, while $f(E)$ is a distribution function determining the occupancy of the central valley [7].

$$f(E) = \left\{1 + R \cdot \exp\left[\frac{-\Delta U}{k_B T_e(E)}\right]\right\}^{-1} \tag{3}$$

where ΔU describes the difference in energy between the central and satellite minima, R is the ratio of densities of states in central and side valleys; (for GaAs: $R = 94$, $\Delta U = 0.31$ eV).

The tested structures, made at the Institute of Electronic Materials Technology in Warsaw, were built of thin alternately laid GaAs layers 7-nm-thick, acting as wells, and $Al_{0.3}Ga_{0.7}As$ layers 6-nm-thick acting as barriers. The total thickness of the PR-MQW thin film was 1.3 µm. They were subjected to proton implantation of different doses. Each sample underwent implantation twice, each time with different protons energies, as shown in Table 1.

* E-mail: blazej.jablonski@zut.edu.pl

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Table 1. Values of energy and doses used during proton implantation in a PR-MQW structure.

Structure	Energy 1	Dose 1	Energy 2	Dose 2
6A	WITHOUT IMPLANTATION			
6B	160 keV	1x10^{12} cm^{-2}	80 keV	1x10^{12} cm^{-2}
6C	160 keV	1.5x10^{12} cm^{-2}	80 keV	1.5x10^{12} cm^{-2}
6D	160 keV	2x10^{12} cm^{-2}	80 keV	2x10^{12} cm^{-2}

The laboratory setup was composed of an argon-krypton laser which generated wavelength $\lambda = 647$ nm, beam intensity control system, measurements of current-voltage characteristics setup and a PR-MQW structure. An electric field was applied parallel to the planes of quantum wells (Franz-Keldysh geometry).
Figure 1 depicts the current-voltage characteristics of the tested structures without illumination. One can see that structure 6A, not subjected to implantation, behaves like a semiconductor, while in the structures 6B-6D the current intensity is smaller and has quasi-linear characteristic.

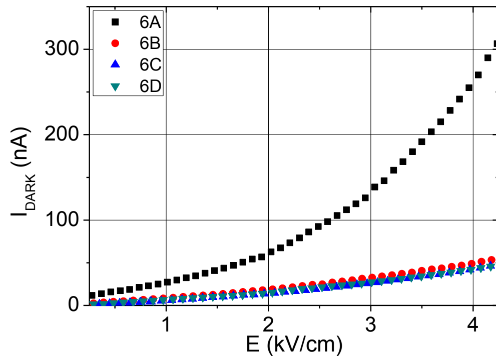

Fig. 1. Dark current as a function of the applied field for the structures, with different proton doses.

Typical current-voltage characteristics of structures illuminated with a homogeneous light beam are presented in Fig. 2.

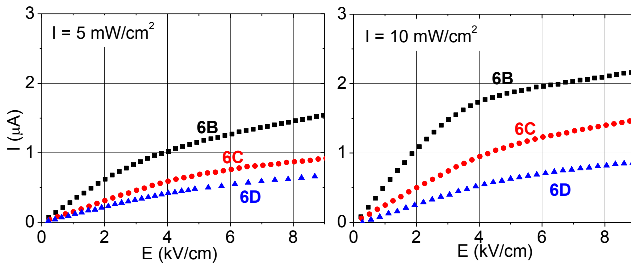

Fig. 2. Photocurrent as a function of the applied field for the structures B, C and D. Light intensity (a) I = 5 mW/cm^2 (b) I = 10 mW/cm^2.

The impact of proton implantation on current-voltage characteristics is visible. The higher the proton dose is, the lower the value of current intensity we get. Assuming that the generation of deep defects is the main effect of implantation, the observed decrease of dark resistivity can be explained by better compensation of shallow defects present in the material while decrease of photocurrent by increasing density of traps for photo-generated carriers. For electric field intensity above critical value E_A, the characteristic curvature related to nonlinear transport of electrons is seen.

The total density of current in photorefractive multiple quantum wells can be written as the sum of electron and hole current densities:

$$j = j_e + j_h = \mathrm{q}[\mu_e(E)n_e + \mu_h n_h]E_0 \qquad (4)$$

where μ_e and μ_h represent the mobility of electrons and holes, n_e and n_h denote the concentration of electrons and holes for homogeneous illumination [3-4, 9]. Carries concentrations in uniformly illuminated structures are:

$$n_e = (\alpha/\mathrm{h}\upsilon)I_0\tau_e,$$
$$n_h = (\alpha/\mathrm{h}\upsilon)I_0\tau_h,$$

where
$\tau_e = 1/\gamma_e N_D^+$, $\tau_h = 1/\gamma_h N_D^0$
are average recombination times for electrons and holes.

Table 2. Material parameters used in calculation.

$\alpha = 5\cdot10^3$ cm^{-1}	interband absorption coefficient
$\gamma_e = 4\cdot10^{-7}$	trapping coefficient for electrons
$\gamma_h = 2\cdot10^{-7}$	trapping coefficient for holes
$\tau_r = 10^{-12}\ s$	energy relaxation time
$\mu_{el} = 5000\ cm^2/Vs$	electron mobility in central valley
$\mu_{eu} = 400\ cm^2/Vs$	electron mobility in side valleys
$\mu_h = 400$ cm^2/Vs	hole mobility
I_0	light density
N_A	concentration of acceptors
N_D	concentration of donors
$N_D^+ \approx N_A$	concentration of ionized donors which are trap center for electrons
$N_D^0 = N_D - N_D^+$	concentration of non-ionized donors which are trap centers for holes

The lifetime of free carriers in photorefractive structures is short, $\tau_e, \tau_h < 100\ ns$ [10]. Owing to this we can assume that excited carriers are almost instantly trapped, which results in $N_D^+ \approx N_A$. The donor compensation coefficient $r = N_A/N_D$, allows estimating whether the transport of carriers is dominated by electrons or by holes. When $r < 0.34$, the transport is dominated by electrons, while for values $r > 0.34$ by holes, which is shown in Table 3.

Table 3. Ratio of hole to electron concentrations in reference to the compensation coefficient.

r	0.01	0.1	0.3	0.333	0.4	0.5	0.7	0.9	0.99
$\frac{n_h}{n_e}$	0.02	0.22	0.85	0.999	1.33	2	4.67	18	198

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Figure 7 presents theoretical characteristics of current intensity as a function of the electric field for different donor compensation coefficients. These calculations were made for homogeneous illumination $\mathrm{I} = 10\ \mathrm{mW/cm^2}$ and the standard value of acceptor concentration $N_A = 3 \cdot 10^{16}\ \mathrm{cm^{-3}}$ [2].

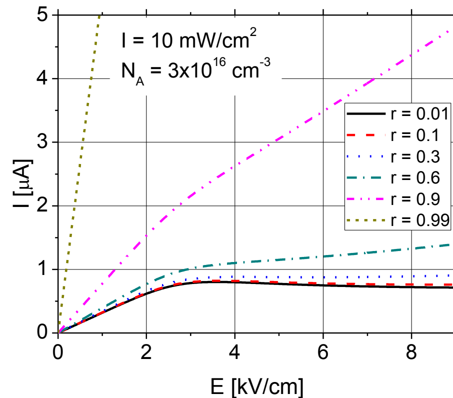

Fig. 7. Photocurrent as a function of the applied field, calculated for the acceptor concentration $N_A = 3 \cdot 10^{16}\mathrm{cm^{-3}}$ and different values of r. Light intensity was $\mathrm{I} = 10\ \mathrm{mW/cm^2}$ and wavelength $\lambda = 647$ nm.

Changes in shape of the curves are visible. As the donor compensation coefficient decreases, the curvatures of the characteristics for $E > E_A$ get larger, which is caused by increasing influence of nonlinearity of electron transport. Figure 8 shows photocurrent-voltage characteristics averaged for samples with the same doses of proton implantation. The solid lines represent analytical solutions, while the dots represent the experimental results, each determined from measurements of few samples.

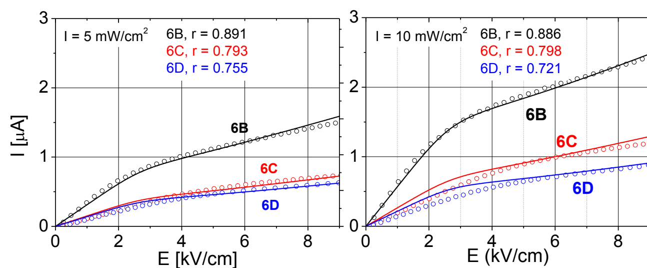

Fig. 8. Photocurrent as a function of the applied field for $N_A \approx 4.5 \cdot 10^{16}\mathrm{cm^{-3}}$, different donor compensation ratio $r = N_D/N_A$ and two values of light intensity: (a) $\mathrm{I} = 5\ \mathrm{mW/cm^2}$, (b) $\mathrm{I} = 10\ \mathrm{mW/cm^2}$. The circles denote measured values, and the plotted lines are analytical solutions.

The comparison of experimental and theoretical curves show that the donor compensation coefficient r depends on proton dose, and for the applied implantation parameters ranges from 0.7 to 0.9, which corresponds to the ratio of hole to electron concentrations $n_h/n_e \approx 5 \div 16$. This indicates the dominance of hole transport in all tested samples.

In summary, the experiments and the theoretical analysis have been aimed at examining the impact of proton implantation in PR-MQW structures on photocurrent-voltage characteristics. By comparing experimental results to the analytical solution describing the intensity of current in the structure, we have estimated an approximate value of the donor compensation coefficient and the type of dominant carriers. All tested structures showed the dominance of holes over electrons. Nevertheless, we have observed the occurrence of nonlinear transport leading to a curvature of the characteristics for electric field intensity above the critical value ($E_A = 3\ \mathrm{kV/cm}$). It has been shown that by varying the doses of protons implanted in the structure we can, to some extent, affect the ratio of electron to hole concentrations. However, this ratio can be adjusted to specific needs only in a limited scope.

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