PHOTOCURRENT SPECTROSCOPY OF SEMI-INSULATING GaAs M-S-M DIODES WITH A NEW CONTACT METALLIZATION

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1. Introduction

Semi-insulating (SI) GaAs became an important candidate for the fabrication of monolithic X-ray and particle detectors [1] due to its good physical characteristics, quality of the base material available on the market and developed device technology. Photoconductivity studies of SI GaAs were published [2-4] during 1970's and 1980's even though most of them deal with old, Cr-doped materials, with rather poor quality [2]. Sharp peak observed at about 890 nm in the spectra at low temperatures was explained by the existence of a free exciton [3, 4]. Applications of GaAs for fabrication of UV detectors have been also investigated [5, 6]. However, the photoelectronic characteristics of the new, undoped, high quality "detector-grade" SI GaAs materials [1] and the influence of electrode metallization in photocurrent spectra together with the electrical transport through M-SI GaAs-M diode structures have to be investigated more deeply, taking also into account the more recent literature on these topics [7, 8]. In particular in ref. [8] it is shown that the use of Mg, a low work function metal, in Mg-SI GaAs-Mg structures gives unexpected low currents at low bias. The observed decrease of the initial current was of about two orders of magnitude in comparison with the common Schottky barrier metallization (such as e.g. Ti/Pt/Au). Reduction of the dark leakage current of such novel devices operating at low (or even zero) bias voltage could improve their photoelectric characteristics, opening new choices in various applications of SI GaAs, including photodetection.

The present work reports on the photocurrent (PC) study of diodes based on bulk SI GaAs with novel contacts including low work function (ϕ) metals, such as Gd and Nd. SI GaAs sandwich-like structures with topside electrodes of Gd/Au, Nd/Au, Pt/Au, and AuGeNi eutectic alloy and bottom AuGeNi eutectic alloy were fabricated. Their electrical and photoelectronic properties are investigated through current-voltage (*I-V*) measurements and PC spectroscopy performed at room temperature in the spectral range of 600–1000 nm in dc regime. It is shown that the observed PC spectra depend on the electrode metals used, applied bias (polarity and voltage), detection regime (dc, ac) and photoexcitation level. A simple physical model, accounting for the photovoltage on the two different metals contacts and the absorption in GaAs bulk, has been used to give a qualitative explanation of the observed spectral characteristics at zero bias.

2. Technology and experiment

Photodetector structures were prepared from bulk undoped SI GaAs wafers (as used previously [7, 8]), with (100) crystallographic orientation and dislocation density of about

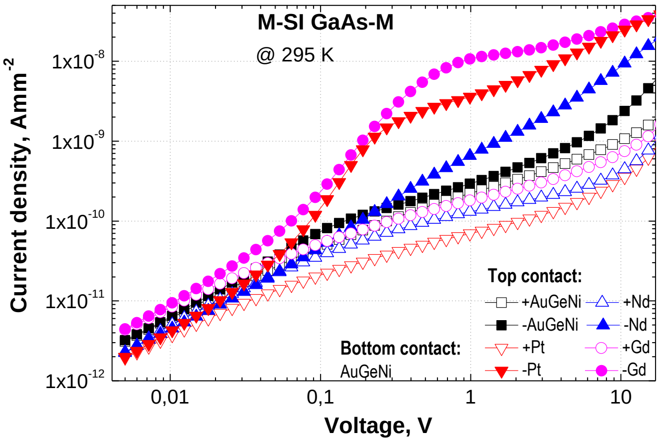

Fig. 1:*Forward and reverse (full and open symbols) I-V characteristics of SI GaAs photodiodes with different semitransparent metallizations measured in the dark and at 295 K.*

Table 1: *Work functions and electronegativity valuesof the metal used as top contact.*

Contact metal	Pt	AuGeNi	Gd	Nd
Work function, eV	5.65	4.6*	3.1	3.2
Electronegativity	2.2	n/a	1.2	1.14

**Estimated value*

3000 cm^{-2} polished from both sides down to (250±10) μm. The material resistivity measured at 295 K (RT) by the van der Pauw method was 1.1×10^{5} Ωm. A backside full-area AuGeNi/Au (40/60 nm) contact was evaporated in a high vacuum system using AuGeNi eutectic alloy. After evaporation the wafer was segmented into fragments of about 1.2×1.5 cm^{2}used for fabrication of different samples. Semitransparent contacts of Gd/Au,Nd/Au, Pt/Au (10/6 nm) and AuGeNi eutecticalloy (16 nm)were then evaporated on the topside. The values of the work functi-on of used metals are listed in Table 1. Just before evaporation the surface oxides were removed in a solution of HCl:H_2O = 1:1 at RT for 30 sec. Finally photodetector structures with contact area of 3-10 mm^2 were cleaved from the wafer fragments, glued and contacted onto a sample holder by sil-ver paste. The *I-V* characteristics of the photodetectors were measured using a voltage source and pA meter Keithley 4155 controlled by a personal computer. The PC measurements were performed at RT using a spectrometer MDR 23 operating in the wavelength range of 600-1000 nm in dc regime and low excitation levels. Polarity of the bias refers to that applied to the *top* semitransparent contact.

The*I-V* characteristics of the samples with different top contacts are shown in Fig. 1. The reverse, low bias branches, which are obtained by positively biasing the top contact, show a sublinear dependence for bias exceeding about 0.1 V. The forward bias branches for Gd, Nd and Pt contacts exhibit a super-linear dependence followed by a sublinear shape starting at bias voltages exceeding about 0.8, 0.5and 0.3 V, respectively. The observed characteristics cannot be directly compared with those published previously [7, 8] because of the different geometry of the contacts. Moreover, since the cleaved samples have different areas (in the range of about 3-10 mm^2), to make easier the comparison among the *I-V* characteristics in Fig. 1 the current density in A/mm^2 is plotted. A detailed description and analysis of the investigated *I-V* characteristics with symmetrical arrangement of contacts will be published elsewhere. PC spectra at zero and +/- 3 V bias voltages (positive bias corresponds to the lower current *I-V* branch) recorded in the photon wavelength range of 600-1000 nm are shown in Fig. 2. The dark current of biased samples, I_d, was extracted from the total measured current I_l. As it can be seen in Fig. 2a, the zero bias signals at wavelength shorter than 880 nm do not exceed +/- 2 nA/mm^2. Positive PC peaks at 880 nm for AuGeNi, Pt and Nd contacts are revealed, while at 890 nm all the structures show negative peaks at −0.5, −4.5 and −11 nA/mm^2 for AuGeNi and Nd, Gd and Pt, respectively. Only the Gd contact exhibits a negative signal in the whole examined spectral region.

The spectra measured with a positive bias of +3 V (reverse branch, Fig. 2b) show positive signals in the full spectral range for all the structures. The highest sensitivity, with a peak value of about 1 μA at 878 nm, is given by the AuGeNi metallization. The other contacts show current peaks (at about the same wavelength) of 400 (Pt), 100 (Gd) and

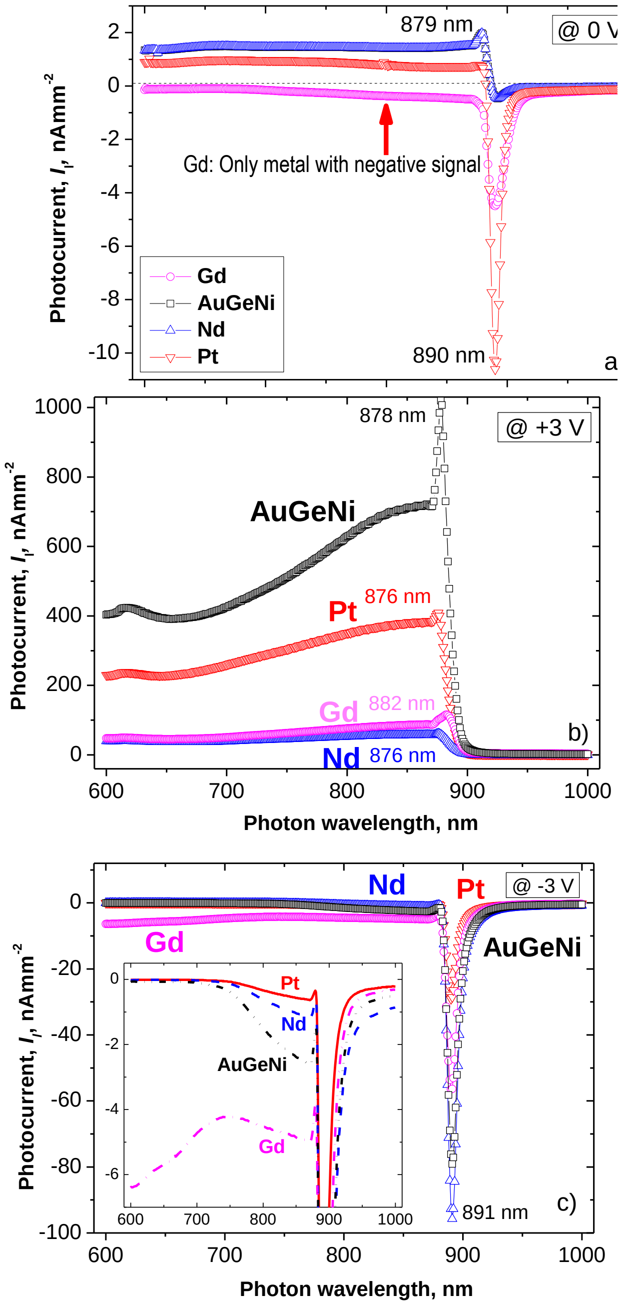

Fig. 2:*Photocurrent spectra of SI GaAs diodes obtained at RT and for different applied biases: zero voltage (a), +3 V (b) and -3 V (c) (polarity on the top, semitransparent contact).*

30 nA/mm^2 (Nd). On the contrary, all the spectra at negative bias of −3 V (“forward” branch, Fig. 2c) give negative signals with a main peak at 891 nm of −100, −80, −55 and −30 nA/mm^2 for Nd, AuGeNi, Gd and Pt contact, respectively. Moreover by inspection of the inset of Fig. 2c, it can be clearly observed that in the wavelength region below about 870 nm the structure with Gd contact shows a much higher sensitivity than the other structures. In particular, for wavelength lower than 700-750 nm the photocurrent of the structure with Gd contact increases, reaching a value of −6 nA/mm^2 at 600 nm, while the signals of Pt, Nd and AuGeNi monotonically decrease and reach values near zero. The fact that the Gd metallization exhibits an increase of the negative signal in this region is very interesting since gives the choice to improve the photodetector sensitivity towards or even in the UV spectral range. Such contact effect on the photocurrent spectral dependence of M-SI GaAs-M structures has never been indicated before.

3. Photocurrent model

Simple evaluation of spectral response was already applied previously to a single heterojunction [9].In this work, calculation of photocurrents in the M-SI GaAs-M structures requires a more complex approach, described below. Although the computing procedure follows well-known photo-voltaic principles, the presence of the second/bottom barrier leads to some interesting results.

The sample geometry is described by the parameters w_1, w_2, and d indicated in Fig. 3. The reflection coefficients R_1 and R_2 define eventual multireflections of light inside the sample and determine, together with the absorption coefficient α and the incident photon flux densityI_0, the intensity of monochromatic light at any position in the sample. It is assumed that the transport through the Schottky barriers is dominated by the thermionic emission theory, characterized by saturation current densities J_{01}, J_{02}, and corresponding ideality factors n_1, n_2. Photo-generated currents I_{ph1} and I_{ph2} consist of excess minority carriers collected by diode 1 and diode 2, respectively. The contributions of carriers generated in the space charge regions (SCRs) as well as in the bulk are considered. The SCRs contributions to photo-generated currents were determined by the

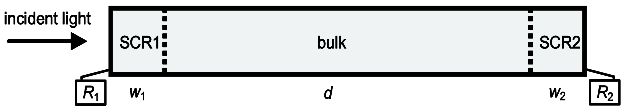

Fig. 3: *Schematic view of an illuminated M-GaAs-M structure. The space charge regions (SCR1 and SCR2) are due to the barriers induced by metal contacts; their widths are denoted by w_1 and w_2. d is the thickness of the bulk region and R_1 and R_2 are the reflection coefficients on the front and rear side, respectively.*

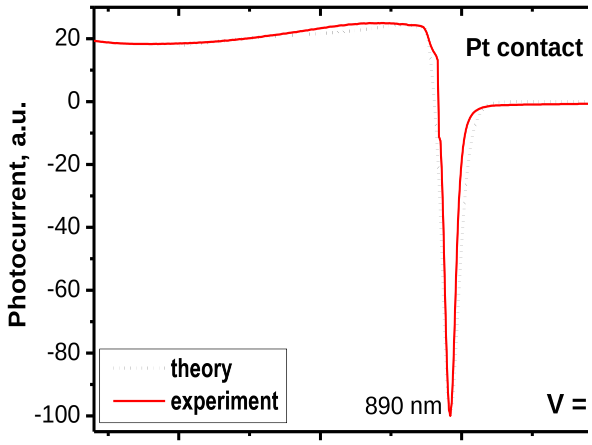

Fig. 4:*Spectral dependence of normalized photocurrent under short-circuit conditions for a sample with Pt metallization. The short-wavelength signal is positive, whereas negative polarity of the photocurrent appears at longer wavelengths (> 880 nm).*

integration of the generation current over SCRs neglecting the carrier recombination. The recombination losses were included subsequently using reduction factors, i.e. collection parameters G_1 and G_2 (numbers between 0 and 1). The contribution from the bulk was calculated accounting for the following steps:(a) Continuity equation at stationary conditions in one-dimensional case leads to a differential equation for excess minority carrier (hole) concentration $\Delta p(x)$; (b) This differential equation is solved using the commonly accepted boundary conditions $\Delta p(0) = 0$, $\Delta p(d) = 0$. Points $x = 0$ and $x = d$ denote the SCRs/bulk boundaries;(c) Diffusion of minority carriers in the bulk takes place in the presence of electric field. This field is assumed to be constant and is derived from the voltage drop across the bulk; a selfconsistent value is found during calculation; (d) Diffusion coefficient and carrier lifetime are approximated by those of minority carriers; for the diffusion length at zero electric field, L_p, it holds $L_p^2 = D_p \tau_p$, where D_p is the hole diffusion

efficient and τ_p the hole lifetime. The bulk contributions to photo-generated currents I_{ph1} and I_{ph2} are just the diffusion currents at points $x = 0$ and $x = d$, respectively. The absorption coefficient of GaAs as a function of wavelength, $\alpha(\lambda)$, was compiled from the literature [10]. Calculating the generation rate of electron-hole pairs, quantum gain β was introduced to avoid an overestimation of the photogenerated currents at long wavelengths (photons may be absorbed but electron-hole pairs are not created). The parameter β is a function of photon energy E and changes from 0 to 1 at the mobility edge E_p. Instead of a step-function, we have used a smooth function varying within small energy range E_s, which is more adequate at non-zero temperature.

The equations describing the *I-V* dependences in the darkness and under illumination can be derived from the Kirchhoff's circuit laws. The total current I_{tot} in an external circuit (dc current mode) is given then by relationship

$$V = \frac{k_B T}{e}\left[n_1 \ln\left(1 + \frac{I_{ph1} + I_{tot}}{J_{01}}\right) - n_2 \ln\left(1 + \frac{I_{ph2} - I_{tot}}{J_{02}}\right)\right] + R_b I_{tot} \,,$$

where V is the applied voltage, R_b is the bulk resistance, and other symbols have their usual meaning. In the darkness, $I_{ph1} = I_{ph2} = 0$, and I_{tot} is simply replaced by I_{dark}. The net photocurrent I_l is then defined as $I_{dark} - I_{tot}$. The current I_{tot} together with the bulk resistance and the bulk thickness define an effective electric field in the bulk which affects the diffusion of minority carriers and, therefore, light-generated currents I_{ph1}, I_{ph2}. Bulk resistance $R_b$depends on excess carrier concentration as well. Thus, aniteration loop must be used to get a self-consistent solution.

The main features of the theoretical results (for $n_1 = n_2$, $w_1 = w_2$, and $G_1 = G_2$) can be summarized as follows:(i) If $J_{01} = J_{02}$ positive short-circuit photocurrent is observed over the whole spectral range; (ii) For $J_{01}>J_{02}$, a sharp negative peak appears together with a decrease of the short-wavelength signal; (iii)By increasing the photon flux density, the negative peak becomes wider and less sharp; (iv) The spectral range where a ~~of~~ significant decrease of the bulk resistance is observed is quite narrow. In the used model, the saturated current densities J_{01} and J_{02} are the fundamental quantities which reflect the kind of contacting metals due to their strong dependence on the barrier height. However, because the real metal/SI GaAs contacts are far from an ideal Schottky or ohmic contact, the approximation based on J_{01}, J_{02} is rather rough and can be applied only at low (close to zero) DC voltages. Despite this limitation, the model yields important qualitative results in the first approximation agreement with the experimental observations. Figure 4 shows an example of spectral dependence of the normalized DC mode photocurrent under short-circuit conditions for a structure with Pt top contact. According to the used model the presence of a sharp negative peak corresponds to the relationship $J_{01}>J_{02}$ pointing to a higher Schottky barrier at the bottom contact.

4. Discussion and conclusions

In contradiction with the results reported in a previous paper [8] devoted to structures with nonsymmetrical contact geometry, the photocurrent characteristics with symmetrical contact area presented here give opposite polarity: lower current spectrum corresponds to *positively* biased top contact, hence negatively biased AuGeNi bottom contact. Higher photosensitivity is also observed for the *positive* polarity: the dc current increases almost 3 orders, while 2 orders of magnitude are found at the same negative bias using the same white light illumination. The photocurrent spectra observed demonstrate high sensitivity to the used contact metallization, which allows partial tuning of the photodiode sensitivity and spectral range. Moreover, the Gd contact show increasing sensitivity toward short wavelength part of the spectra such giving better choice for application even in the UV region. Sharp peak observed at 890 nm in a first approach correspond to the used simple model of two back-to-back metal contacts accounting absorption in SI GaAs bulk. Hence, previous explanation of the peak as a result of free exciton seems to be questionable in the light of these observations.

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