PECULIARITIES OF METAL CONTACTS ON SEMI-INSULATING GaAs: ELECTRICAL, PHOTOELECTRONIC AND XPS CHARACTERIZATION

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Received 11 May 2015; accepted 20 May 2015

1. Introduction

Semi-insulating (SI) GaAs has become one of the interesting candidates mainly for the fabrication of nuclear detectors particularly monolithic detector arrays in X-ray imaging [1] due to its good physical characteristics including attenuation factor, quality of the base material, and developed material technology. Applications of SI GaAs in the field of detection in ultraviolet (UV) spectral region have been also investigated [2]. Important improvement in the radiation detector technology is related to the "non-alloyed" ohmic contact technology introduced by Alietti et al. [3]. Performance study of SI GaAs radiation detector with implanted ohmic contact presented Bertolucci et al. [4]. Analysis and possible interpretation of the electrical charge transport in low bias region of SI GaA-based diodes became an object of our recent paper [5]. Barrier metallization on conductive *n*- or *p*-type GaAs are summarized e.g. in monography of Rhoderick [6]. Additional papers report on different blocking contact metallization in n-GaAs using e.g. Ir-Al, Pt, Ag (deposited by MBE), Cu, Ag and Pt produced by electrochemical deposition giving a barrier height of 0.95 eV, 0.98 eV, 0.991 eV, and 1.15 – 1.2 eV, [7-10], respectively. These bariers are higher than obviously used Ti/Pt/Au metallization (typical barrier height 0.78 eV). In addition, following papers are devoted to the surface treatment prior the metal deposition increasing the barrier height such as e.g. Se, PH_3 plasma treatment, or sulfur passivation [11-13], respectively. It should be noted, that a comprehensive study of barrier contacts or surface treatment prior the metal deposition to SI GaAs, is not available. Generally preferred SI GaAs detector barrier metallization presents Ti/Pt/Au, or Ti/Au e.g. [1-4]. Our previous study [14] reported on *I-V* characteristics of SI GaAs structures with Ti/Pt/Au blocking contact coupled with In, Mg and Gd full area quasi-ohmic contacts. It should be noted that formation of the interface M-SI GaAs seems to be different of conductive *n*- or *p*-type GaAs. Hence, the electrical charge transport through the M-SI GaAs presents an interesting physical and application study.

The present work reports on peculiarities in the charge transport observed with novel electrodes applied to SI GaAs in relation to our previous results. The novel electrode uses a metal with rather low work function (such as e.g. In, Mg, Gd) used in our previous paper [14] as a quasi-ohmic contact. Fabricated structures with the small "blocking" top contacts and full area quasi-ohmic backside metallization, are compared with full area contacts on both sides. Structures based on the same "detector-grade" SI GaAs are characterized by the current-voltage (*I-V*) measurements, photocurrent spectroscopy (PCS), and X-ray photo-emission spectroscopy (XPS). We observed an anomalous lowering of the reverse current at low bias voltages (<10 V) for electrodes formed by Gd and Mg. Possible explanation of the observed effects is presented and applications utilizing the investigated effect are discussed.

2. Technology and experimental details

Detector structures were prepared from bulk undoped SI GaAs wafer grown by vertical gradient freeze (VGF) method with (100) crystallographic orientation and dislocation density of about 3000 cm^{-2} polished from both sides to (250±10) µm. Resistivity and the Hall mobility measured by the van der Pauw method at 295 K give values of 1.8×10^7 Ωcm and 7060 cm^2/Vs, respectively. The values fulfill key requirements for a "detector-grade" bulk SI GaAs [1]. The wafer was segmented into fragments used for fabrication of two sets of samples (each kind of samples used an area of about 200 mm^2). Samples of set A have square electrodes of 0.5 mm size formed by photolithography masking onto topside using Ti/Pt/Au (10/40/70 nm), eutectic alloy AuGeNi/Au, In/Au, Mg/Au and Gd/Au (40/80 nm) and full area Ti/Pt/Au metallization as a backside quasi-ohmic contact. Samples of the second set B have different full area semitransparent electrodes on the topside using Ti/Pt/Au, AuGeNi/Au, Gd/Au and Nd/Au (10/5 nm) and full area AuGeNi/Au (40/80 nm) quasi-ohmic contact on the backside. List of the used metal work function is presented in Table 1. Just before evaporation the surface oxides were removed in a solution of $HCl:H_2O = 1:1$ at room temperature (RT, 300 K) for 30 sec. The metal contacts were evaporated in a dry high-vacuum system. *I-V* characteristics of the prepared structures were measured with Keithley 237 source controlled by personal computer. Measurements were performed at RT in the dark using an electrically shielded probe station with temperature stabilization and tip contact on the topside. The PCS was performed at RT using a single gating spectrometer MDR 23 operating at a low excitation in d.c. regime in the wavelength range of 600-1000 nm. A pyroelectric detector was used for a relative calibration of the incident light. The bias polarity is that applied to the *top* semitransparent contact. The XPS signals were recorded using Thermo Fisher Scientific apparatus equipped with a micro-focused, monochromatic Al K-α X-ray source (1486.6 eV). An X-ray beam (12 kV/6 mA) of 400 nm size was used. Signals from narrow regions were collected using the snapshot acquisition mode (150 eV pass energy), enabling rapid collection of data (5 s per region). Charge compensation was achieved with the system of flood gun. Depth profile analysis was done with ion gun (1.4 µA of 2 keV Ar$^+$ ions over 8 mm^2). The Thermo Scientific Avantage software, version 4.88 (Thermo Fisher Scientific), was used for digital acquisition and data processing. Spectral calibration was determined by using the automated calibration routine and the internal Au, Ag and Cu standards supplied with the K-α system.

Tab. 1. *List of the metal used work function.*

Metal:	Pt	Ti	AuGeNi	In	Mg	Gd	Nd
Work function, eV	5.65	4.33	4.6*	4.12	3.68	3.1	3.2

* *Estimated value*

3. Results and discussion

Measured *I–V* characteristics of fabricated structures measured at RT in the dark are shown in Fig. 1. The straight dashed lines correspond to the calculated linear-ohmic dependence given by the bulk material resistivity and the structure geometry with the lowest resistance of about 4×10^7 Ω. The initial linear part of the measured *I-V* characteristics of set A gives resistance of about 1.2×10^8 Ω for all metals with exception of Gd and Mg with the highest value of about 2.2×10^{10} Ω (the straight dot line). Situation in samples of set B is completely different: the lowest initial resistance of about 9×10^8 Ω corresponds to Gd/Au contact. Resistance of other contacts increases to the maximal value of about 2.5×10^9 Ω for Pt/Au. The highest resistance observed with small Gd and Mg contacts (set A) exceeds by

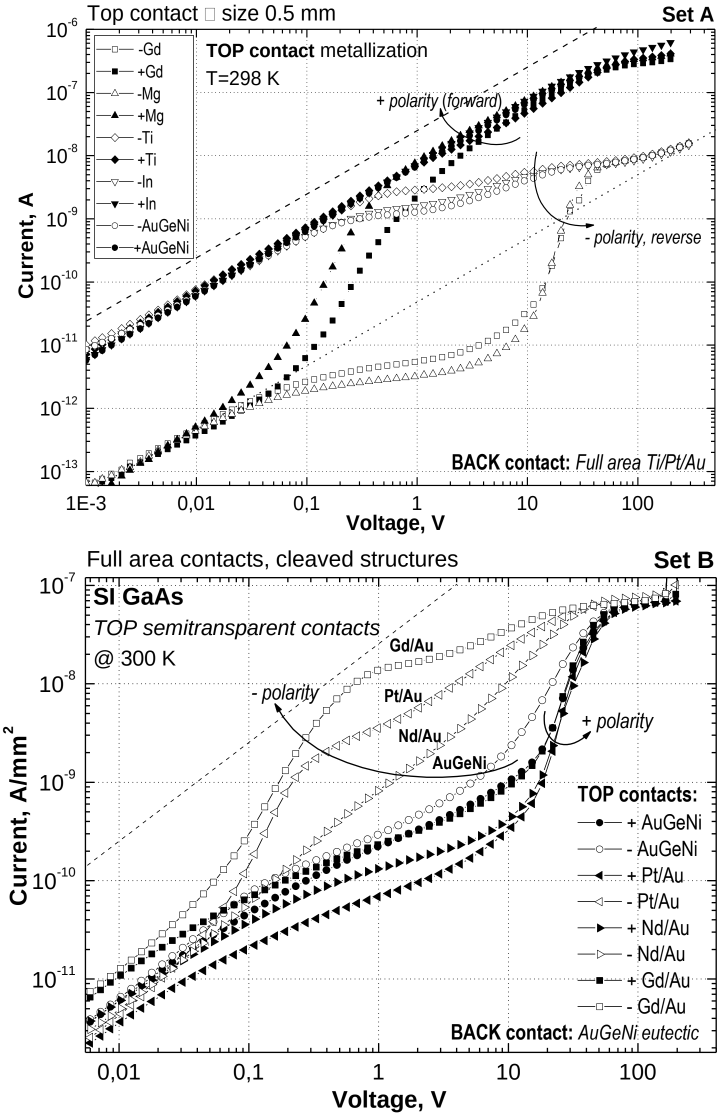

Fig. 1: *I-V characteristics of the fabricated SI GaAs structures: different top square $0.5\times0.5\ mm^2$ contacts (Ti/Pt, AuGeNi, In, Mg, Gd) and Ti/Pt/Au full area bottom contact (set A); different full area top semitransparent contacts (AuGeNi, Nd/Au, Pt/Au, Gd/Au) and AuGeNi eutectic full area bottom contact (set B).*

about one order of magnitude the value corresponding to the intrinsic resistivity of GaAs ($\sim2\times10^8\ \Omega$cm). Such observation indicates a free carrier extraction from the bulk region. Similarly, higher base apparent resistivity was predicted by Manifacier and Ardebili [15] for a p^+-SI GaAs-n^+ structure based on deep trap-dominated overcompensated material. In general, we can conclude that used contact metallization and its topology has serious influence to the initial resistance of M-SI GaAs device, i.e. an apparent base material resistivity. The full area contacts used in the case of samples of set B give more clear physical picture: there is no influence of an additional rectifier effect induced by the different areas of the top- and backside contacts. This is clearly confirmed in high bias voltage region, >100 V, where current is almost independent of used metallization. In opposite, samples from the set A show ratio between the forward and reverse currents at high bias voltages in a value corresponding to the ratio in contacts area (~20). As for the forward characteristics, structures with Gd and Mg metallizations (set A) and Gd/Au and Pt/Au (set B) exhibit a superlinear injection region ($i \sim V^2$) after the initial linear part, over about ~0.1 V. The reverse bias characteristics show saturation region between about 0.1-3 V. The saturation is observed for all metals, while for Gd and Mg the current is substantially lower by about 2-3 orders of magnitude in bias voltage region <10 V. The observed first sublinear part of the reverse characteristics roughly corresponds to the value of the saturation current I_s controlled by the thermionic emission: in

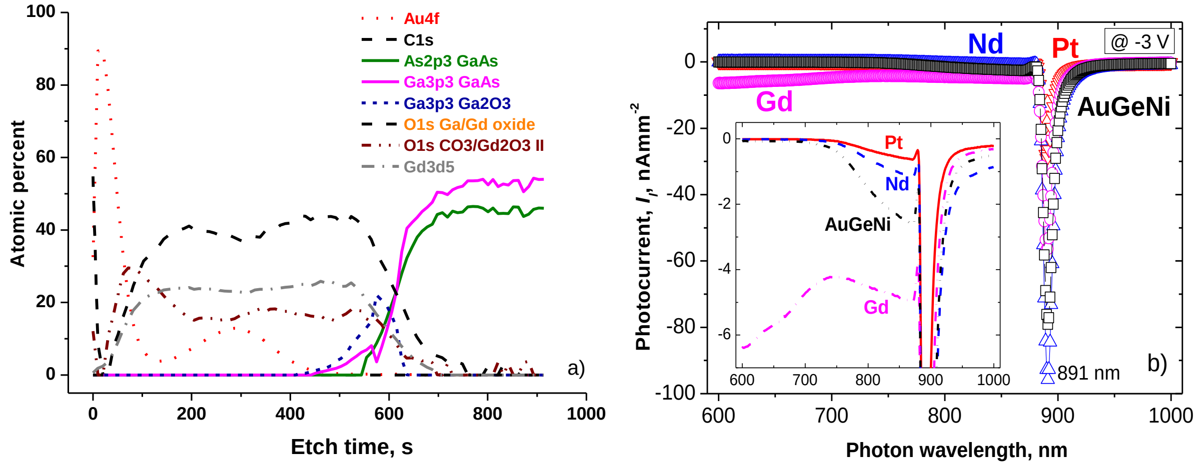

Fig. 2: *XPS signals observed from Gd/Au-SI GaAs interface (a) and PC spectra of SI GaAs structures with different top contacts in the 600-1000 nm spectral range at a bias of -3 V (b).*

the case of set A for all curves, while in the case B it is valid for AuGeNi metallization only. For other metallization the polarity is inverted comparing to set A: *"reverse"*, i.e. lower current branch is observed at *positive* bias on topside. Possible explanation is related to double injection from contacts into SI GaAs and interaction of injected carriers with free carriers in quasi-neutral base region. Such is created an original free charge state in the base controlled by particular combination of electrodes. The second sublinear part at voltages over 20 V, which represents obvious operation bias region of a radiation detector, is characterized by the saturation drift velocity at high electric field [16]. Finally, for reverse bias over about 100 V, the current is almost identical for all structures (set B). Described observations are in contradiction with the standard expectations. For better understanding the chemical composition of Mg- and Gd-SI GaAs interfaces were evaluated by the XPS. Example of the result for Gd-SI GaAs is shown in Fig. 2a. For summary, at the interface we detected formation of an insulator oxides, particularly Gd_2O_3 and MgO, without presence of Gd or Mg in the metallic form. In addition, the cover Au layer partially diffused into oxides. Such oxides present wide band-gap insulators leading to creation of a heterojunction, hence quantum well (QW), at the Mg- or Gd-SI GaAs interfaces. 2DEG present in QW is formed preferably by electrons from the SI GaAs bulk, because electrons flow from the top Au contact is blocked by the insulator layer. This is possible explanation of the electron deficiency in the neutral SI GaAs bulk or the observed increase of its apparent bulk resistivity. Due to such circumstance, generally accepted pinning of the Fermi level at the M-GaAs interface (e.g. [6]), cannot be present there.

Extremely low dark current observed with Gd and Mg contacts could improve sensitivities of SI GaAs photodetectectors or another sensors. Photocurrent spectra of structures with semitransparent top contacts (set B, bias -3 V) are shown in Fig. 2b. As can be seen, the spectra depend on the particular contact metallization and short wave sensitivity of structure with Gd contact interestingly increases (inset of Fig. 2b).

Conclusion

Study of a new kind of contact metallization on SI GaAs is presented. The new contact uses metals with low work function, namely In, Mg, Gd and Nd. For Mg and Gd an anomalous decrease of the reverse current by about 2 orders of magnitude at a bias voltage <20 V has been observed. Interface chemistry inspected by the XPS show presence of Gd and Mg insulation oxides, particularly Gd_2O_3 and MgO, at the M-S interface, leading to formation of a heterojunction Au-*I*-SI GaAs. Related 2DEG presented in created QW is filled preferably by electrons from bulk because their flow from the top Au contact is blocked by insulator. This explains the observed anomalous lowering of the reverse dark current what can be utilized mainly in performance improvement of photodetectors, photovoltaic devices and different sensors. Follow-up study will be necessary for full understanding of the indicated anomalies in chemistry of the M-SI GaAs interface, related electrical charge transport and finally their application in novel devices.

Acknowledgement

This work was supported in a part from grants of the Grant Agency for Science Nos. 2/0167/13 and 2/0175/13 and grant of the Slovak Research and Development Agency No. APVV-0321-11.

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