UNEXPECTED CURRENT LOWERING OF Mg CONTACT ON SI-GaAs

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1. Introduction

The controlled tuning of semiconductor device operation characteristics at the technological preparation stage, including electronic charge transport properties, is a crucial task in electronic device engineering. Focusing attention on the diodes with blocking Schottky barrier, the key steps in the formation of these devices include the selection of a metal contact and a contact deposition technique. Semi-insulating GaAs (SI-GaAs) has become a material of choice in X-ray detection [1], a potential candidate for UV detection [2] and THz device applications [3,4]. Concerning the simple metal contacts on SI-GaAs, their use is advantageous with respect to the more conventional p^+/n^+ contacts, due to their lower cost and easier preparation procedures, moreover metals do not significantly affect the original very low concentration (~10^7 cm^{-3}) of free carriers in the SI-GaAs base. Thus, diodes with metal contacts based on SI-GaAs are worth of detailed investigation.

In general, the Fermi-level pinning is known to be operative at the metal/GaAs interface (e.g. [5,6]), and the same is expected in SI-GaAs. Some evidence on the possible modification of the transport properties in metal/SI-GaAs/metal (MSM) diodes, by using various large-area bottom contacts, including metals with a low work-function (φ), has been reported [7,8]. In particular, the low-bias current below 0.1 V was found to belower, by a factor of ~1.5-5, compared to the expected bulk ohmic current [8], and the deviation increased for decreasing φ, in contradiction with the thermionic emission (TE) predictions [9].It must be pointed out, that the physics of electrical charge transport in M/SI-GaAs devices is not well understood and documented yet, despite the role it plays, e.g., in the interpretation of the particle and radiation detector properties (e.g. [1,10-13]). The difference between the bulk and apparent resistivities of SI-GaAs (p-*v*-n structure) was reported already in the pioneering work by Ilegems and Queisser (1975) [14]. The work of Baldini et al. (2000) [12], in our opinion the most important example in this respect, reports *I-V* curves of the M/SI-GaAs/n^+Schottky diodes as a function of the substrate acceptor concentration. The data reveal a constant initial resistance independent of the doping concentration varying between 10^{14} and 10^{17} cm^{-3}.The conventional explanation of "ohmic-bulk limited" (OBL) transport (see also [10,11]), adopted also by the authors, fails here. The controversy, to the best of our knowledge, has not been satisfactorily explained to date. Some guidance has been given by the modeling of Manifacier and Ardebili (1995) [15]. In case of the p^+/SI-GaAs/n^+ diode, they predicted a low-bias resistivity that is higher, than the resistivity of SI-GaAs bulk for a standard device length. Clearly, the data in existing literature are not systematically comparable, and remain without interpretation or misinterpreted. We are not aware of any references devoted to study of the SI-GaAs based barrier diodes with metal contacts on both sides, that would help to explain the observations reported in Ref. [8].

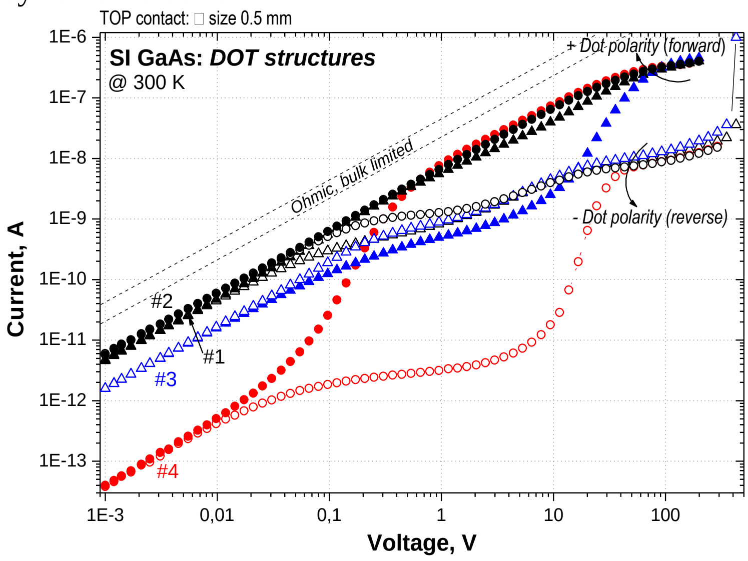
The studied non-symmetric sandwich-like structures consist of large-area bottom and small-area top-contact metallizations, including the standard AuGeNi and Ti/Pt, as well as the non-standard low work-function metal, Mg. The devices are assessed in terms of the resulting *I-V* characteristics. These reveal a strong dependence on the varied device parameters, allowing to tailor a device with exceptional and unexpected (in light of the previous work [8]) current lowering by nearly two orders of magnitude, in diode where the low work-function Mg metal is used in the role of a blocking small-area top contact. The significant current lowering induced by such contact points out the need to reconsider applications of SI-GaAs in devices with a low-current requirements.The observed high resistance is rather unexpected in light of the conventional transport mechanisms based on the OBL and TE models [7-13]. It will be shown below, that these models are not able to give a general interpretation of the transport in SI-GaAs diodes. The estimated OBL current, is never reached in the studied samples, including the so-called "standard" sample with a small top Ti/Pt and bottom large-area quasi-ohmic AuGeNi contacts. Alternative explanations of the SI-GaAs transport, qualitatively consistent with the data reported, are therefore discussed.

2. Experiment

The studied MSM structures, used for measurements, were prepared from a wafer (polished from both sides to (250±10) μm) of undoped SI-GaAs grown by the vertical gradient freeze method with (100) crystallographic orientation and dislocation density of about ~3000 cm^{-2}. The corresponding resistivity and the Hall mobility, measured by the van der Pauw method at temperature T=300 K (RT), were found to be $(1.1\pm0.2)\times10^7$ Ωcm and 7060 cm^2/Vs, respectively, i.e. the material could be classified as “detector-grade” [16]. Four types of samples were obtained by using different combinations of metal contacts: Pt/Ti/SI-GaAs/AuGeNi (#1), AuGeNi/SI-GaAs/Ti/Pt (#2), Pt/Ti/SI-GaAs/Mg (#3), and Mg/SI-GaAs/Ti/Pt (#4). The structures, schematically depicted in Fig. 1, consisting of small top square barrier contacts (0.5×0.5 mm^2) and large-area bottom (quasi-ohmic) contacts (~10 mm^2) were prepared by optical photolithographic masking and lift-off technique. The Ti, Pt, Mg and AuGeNi (eutectic alloy) were evaporated in a dry high-vacuum system to form layersthick 10, 20, 40 and 40 nm, respectively, immediately after the removal of surface oxides in a solution of HCl:H_2O=1:1 at RT for 30 s. All contacts were finally covered, in situ, by 60 nm thick layer of Au. The presence of a thin native oxide layer at the SI-GaAs surface, before the metal evaporation, is unavoidable due to the short air-exposition of the samples after theoxide removal step. Forward and reverse *I-V* characteristics of the prepared structures were measured at RT in the dark and electrically shielded and thermally stabilized (±0.5 K) probe station using a source Keithley 237 controlled by a personal computer. The electrical probe tip, setting the bias polarity, was connected to the topside contact.

3. Results

The measured *I-V* characteristics for the set of four studied samples are reported in Fig. 1. The initial low bias, OBL characteristics, estimated on the basis of the substrate resis-tivity, and the measured sample size (assuming the effective small contact area ~1 mm^2 due to the spreading field) are indicated by the dashed lines, with the mean value $R_{OBL}=(2.75\pm0.5)\times10^7$ Ω. For the “standard”sample (#1) with Ti/Pt (φ~5 eV [17]) at the top and AuGeNi eutectic alloy (φ~4.7 eV) at the bottom side, the current is about four times lower than the value of the OBL estimate, and the initial resistance is found to be 2.2×10^8 Ω. The structure #2, with AuGeNi at the top and Ti/Pt at the bottom, shows similar characteristics as those of the sample #1, as expected, anda slightly higher current which gives resistance 1.8×10^8 Ω. The replacement of the bottom AuGeNi metal of the "standard" sample (#1) with a low work-function Mg metallization(φ~3.7 eV [18]) reduces the current by half an order of



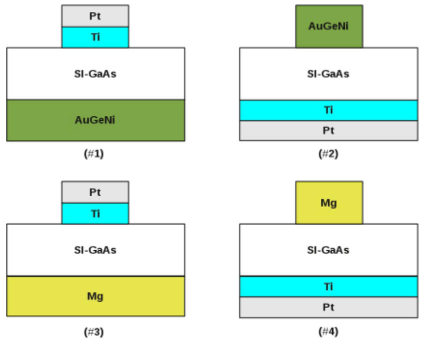


Fig.1:*Measured I-V characteristics of the fabricated MSM structures on SI-GaAs (left) and schematic contacts arrangement (right).*

magnitudeand the initial resistance increases to 6.5×10^{8} Ω. The lowest current is observed in case of the sample #4, which has a small Mg contact at the top and Ti/Pt at the bottom. In this sample, the low-bias current lies an additional order of magnitude below the current measured on the sample #3 and almost two orders of magnitude below the current detected in the "standard" sample, reaching the remarkable initial resistance of $(2.5\pm0.5)\times10^{10}$ Ω. Another way of looking at the result of huge current decrease in case of the sample #4, is following the sequence #2→#4. Here, both samples have the same bottom Ti/Ptmetallization. In sample #2 with AuGeNi small top contact, the current is highest, whereas its replacement by Mg leads to the current decrease by more than two orders of magnitude, giving the lowest current.

4. Discussion

The findings from the above reported results may be summarized:

i) failure of the OBL model; the initial resistances for all samples are higher than those expected for the SI-GaAs bulk-mediated transport, i.e. they are inconsistent with the OBL mechanism. The present results, together with those of Baldini et al. [12], extend the data-set which allows to prove that the OBL mechanism is not applicable as a general explanation of the low-bias transport in SI-GaAs diodes.

ii) Breakdown of the TE model; the TE saturation current is expected to increase with the decreesing φ, as $I_s \propto exp(-q\varphi/kT)$, where q is the elementary charge, k is the Boltzmann constant and T is the absolute temperature. Comparing behavior of the samples #1 and #2, i.e. the change of the blocking contact metal from Ti/Ptto AuGeNi, the TE model holds and the current rises as expected. In contrast, in the sample #3, the reverse polarized large-area Mg contact blocks the current more effectively than the small Ti/Pt contact (Fig. 1). Another deviation from the TE model is observed in the samples #3 and #4, where the reverse and forward curves in the *I-V* characteristics start to diverge, due to onset of the injection that starts well below 3kT, at about 0.006 V (Fig. 1).

iii) Key role of the Mg metallization; as mentioned above, while interchange of the Pt/Ti and AuGeNi metallizations causes only minor changes of the resistances, if the Mg contact is involved, a significant reduction of the current is observed. The highest measured resistance (#4) corresponds to a SI-GaAs apparent resistivity of about 10^{10}Ωcm (RT), significantly exceeding the resistivity of the intrinsic GaAs (~3.3×10^{8}Ωcm, RT). We believe, that the main contribution to the observed increase of the resistance is not due to the presence of a thin amorphous oxide layer (referred to as MgO in the following), that we expect to be present at the interface between Mg and SI-GaAs. Considering, that the typical dielectric strength of MgO is about 2×10^5 Vcm^{-1} [19], and by assuming the MgO thickness of 5 nm (overestimate), its breakdown voltage should then reach only about 0.1 V. However, it is seen in Fig. 1 that the applied bias easily exceeds 100 V also with Mg metallization, ruling out the main contribution of the oxide. In addition, in case of the sample #4, estimated resistance of the ideal MgO layer (assuming thickness of 5 nm and resistivity of $10^{14}\Omega$cm [19]) under the top Mg contact, is found to be ~2.5×10^8 Ω, i.e. hundred times less than the calculated resistance of the sample. It follows that the increase of the resistivity in our samples must be caused by another effect.

iv) Importance of the device asymmetry; comparing samples #3 and #4, the current lowering of about 80 times, does not correspond to the effective (i.e. taking the spreading field into account) change in the contact area of about ten times. Thenon-linear and thus the non-trivial relationship between the Mg contact area and the total observed current, is furthermore corroborated by the fact that in the sample #3,in contrast to all the remaining samples, the forward current in a bias voltage region ~0.02-15 Vis lower than the reverse one. It follows that asymmetry of the device is not at all negligible and should be explicitly taken into account in a realistic modeling.

In summary for the Mg/SI-GaAs contact, we tentatively suggest the following scenario: the observed current is lower than expected, implying downwards band bending, possibly caused either by unpinning of the Fermi-level or presence of the dipole near the contact (dipole-like response is observed). A quasi-degenerate potential well near the contact is formed, accommodating free charge carriers from the bulk. In addition, the EL2 and shallow donor levels, pushed below the Fermi-level in the contact region, require a significant amount of electrons for their neutralization. The electrons come preferentially from the bulk SI-GaAs due to the presence of a thin Mg oxide layer (possibly giving rise to a dipole) that prevents charge flow from the metal. The charge neutrality condition requires an equivalent extraction of both types of carriers from the neutral SI-GaAs towards the contact region (cf. [20,21]). Thus, the free carrier concentration reduction in the SI-GaAs base leads to the observed high apparent resistivity. To date, SI-GaAswas mostly used in radiation detectors operating rather at high-voltages. Predictions based on the conventional concept of the OBL low-bias transport limit its use in devices where the low leakage current is of key importance. Now, the SI-GaAs applications should be reconsidered, as follows from the proven possibility of the current lowering by orders of magnitude. In addition to X-ray detectors, SI-GaAs may now be beneficial in short-base photonic devices operating at low bias, interdigitated planar structures such as photodiodes (cf. [2]), fast opto-switches, solar cells, and various physical sensors.

5. Conclusions

Four SI–GaAs surface barrier diodes with different contact metallizations and/or contact areas were prepared and characterized interms of the *I–V*measurements. The possibility of tuning their performance has been demonstrated by virtue of the deviceengineering, involving a low work-function Mg metallization and manipulation of the contact area. A device with a remarkable currentlowering, by almost two orders of magnitude with respect tothe ‘‘standard‘‘ sample, was prepared. Such a possibility opens new application choices for SI–GaAs not recognized before. We suggest its use, with appropriate metal contact/s, in devices with a lowcurrentat low-voltage requirements, such as photonic devices, photodiodes ordifferent physical sensors. The reported data and evidence from the existing literaturerule out the widely accepted mechanism of ohmic/bulk-limited and thermionic emission transport as general rules for theinterpretation of the low-bias regime in SI–GaAs diodes. The strong blocking ability of the low work function Mg contact was attributed to the downwards band bending, near contact charge carriersaccumulation and the corresponding lowering of the bulk SI-GaAs free carrier concentration.

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