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# Characterization of $A^{III}B^{V}$ epitaxial layers by scanning spreading resistance microscopy

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One of the electrical characterization techniques of semiconductor structures with nanometer spatial resolution is scanning spreading resistance microscopy (SSRM). The applicability of SSRM technique for characterization of GaAs structures with *n*-type doping fabricated by metalorganic vapour phase epitaxy (MOVPE) was examined. The influence of scaling effect on the nanometer size AFM tip–semiconductor electrical characteristics was described. The results of characterization of device structure of magnetic field sensitive field effect transistor were presented.

Keywords: scanning spreading resistance microscopy (SSRM), spreading resistance, GaAs, atomic force microscopy (AFM).

## 1. Introduction

Nowadays, the advanced modes of atomic force microscopy (AFM) allow not only topography measurements in nanoscale resolution but also local characterization of various material parameters, for example: mechanical, electrical, thermal and magnetic. One of these techniques is scanning spreading resistance microscopy (SSRM). In this technique, by applying DC voltage to a conducting tip and measuring the value of current flowing during scanning the sample surface, the resistance of such system could be estimated. Measured resistance consists of several components connected in series: spreading resistance, AFM tip–semiconductor surface contact resistance, resistance of AFM tip, bulk resistance of a semiconductor and short contact resistance. The value of spreading resistance depends on the resistivity of the sample, thus local parameters of the investigated semiconductor as composition, carrier concentration and structural defects occurrence could be evaluated. This technique is successfully applied for qualitative and quantitative characterization of silicon structures with one nanometer resolution [1]. It is possible due to a characteristic property of silicon which is a phase transition to metallic phase under pressure of 10–12 GPa [2]. Such pressure occurs in silicon, in the volume directly under AFM tip during scanning in SSRM measurements. That leads to the creation of ohmic contact between the AFM tip and semiconductor. The resistance of the contact is much smaller than the spreading resistance. In case of compound semiconductors, complex contact effects on the AFM tip–material interface do not allow for evaluation of spreading resistance directly from measured *I–V* characteristics. In this paper, characteristic features of AFM tip nanocontact to *n*-type GaAs is presented and discussed.

## 2. Experiment

Measurements were performed using Veeco Multimode V Atomic Force Microscope with SSRM mode. The silicon tips coated by boron doped diamond were applied. This coating is fully conductive and commonly treated as metallic [3]. Test samples were scanned with speed of 1 μm/s and force applied to the tip of about 200 nN. The GaAs samples were prepared by MOVPE epitaxy and consisted of four *n*-type layers with different carrier concentration deposited on an insulating substrate. Figure 1 presents the profile of carrier concentration measured by electrochemical CV method (E-CV) with marked layers: A ($n = 2.6\times10^{18}$ cm$^{-3}$), B ($n = 2.1\times10^{17}$ cm$^{-3}$), C ($n = 3.3\times10^{16}$ cm$^{-3}$), D ($n = 9.3\times10^{17}$ cm$^{-3}$) and E (insulating substrate).

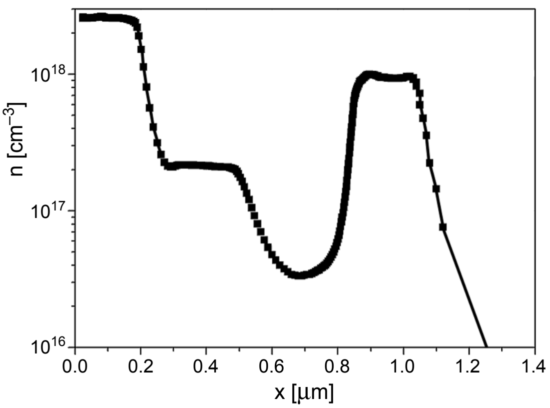


Fig. 1. E-CV carriers concentration profile of GaAs test structure.

The SSRM profiles were obtained by scanning the surface of a cleaved sample. Two different types of short contact formation to the sample were utilized: AuGe/Ni/Au metallization and GaIn eutectic mixture.

## 3. Results

Figures 2 and 3 present spreading resistance profiles of *n*-GaAs sample for two types of short contact formation. In both cases, the acquired results depended on polarization voltage applied to the tip.

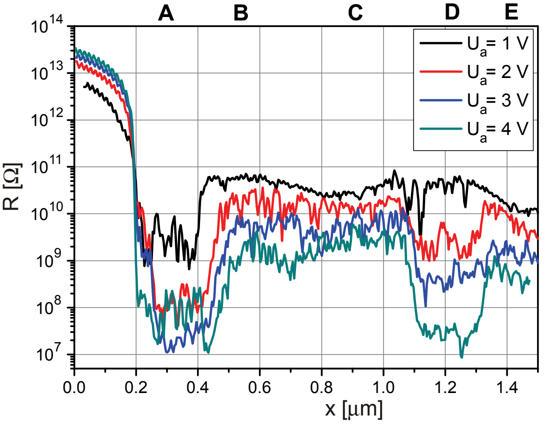


Fig. 2. SSRM profile of GaAs structure with short contact formed by GaIn eutectic mixture placed on top of the sample.

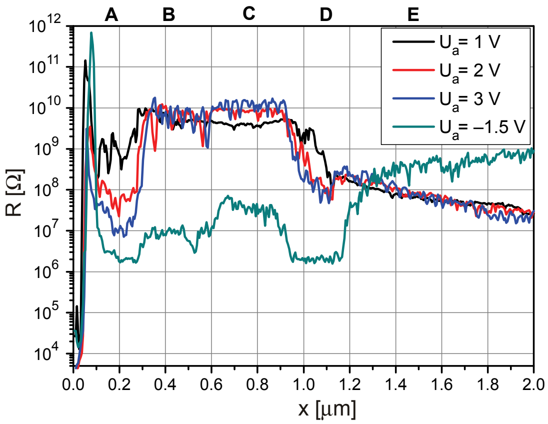


Fig. 3. SSRM profile of GaAs structure with short contact formed by AuGe/Ni/Au metallization placed on top of the sample.

The largest contrast and smallest noise were obtained for voltages in the range of 2–3 V (the contrast is defined as a value of change in spreading resistance due to the alteration of carrier concentration). This experimentally estimated value of an optimal voltage level was confirmed by other SSRM measurements of various AlGaAs/GaAs structures, not presented here.

Current–voltage characteristics of the contact of AFM tip to GaAs surface are presented in Figs. 4 and 5. Characteristics of contacts to layers of different carrier concentrations (A, B, C, D, E) are marked by different colors. The *I–V* curves obtained for both types of short contacts were similar and presented non-linear and rectifying properties. One could distinguish polarization in forward direction (negative voltages) and reverse direction (positive voltages) of these characteristics. Additionally, there was a difference in *I–V* curves shape for polarization in reverse direction: in case of

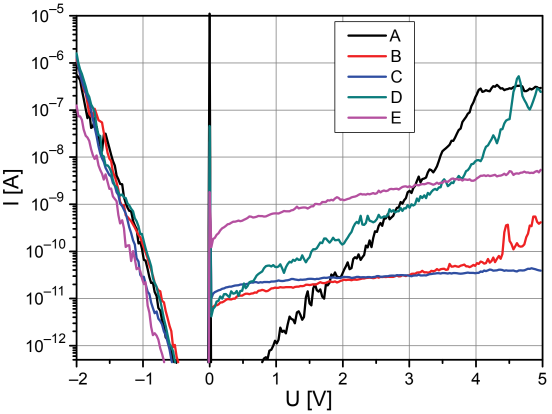


Fig. 4. *I–V* characteristics of AFM tip–GaAs surface contact. Sample with short contact formed by GaIn eutectic mixture.

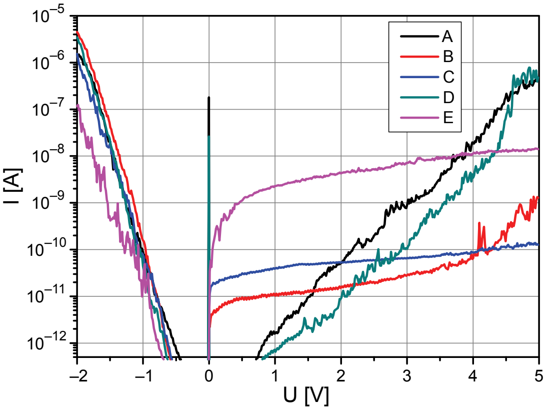


Fig. 5. *I–V* characteristics of AFM tip–GaAs surface contact. Sample with short contact formed by AuGe/Ni/Au metallization.

contact to higher doped layers (A, D) progressive increase in current with voltage occurred, when in case of contact to layers with lower concentration (B, C, E) some saturation of current could be observed (in semilogarithmic scale of graph).

These differences exclude the application of the calibration curves (the dependence of measured resistance on carrier concentration in the sample) presented in Fig. 6 for quantitative characterization of GaAs layers.

In case of silicon, such calibration curves have monotonic, linear character and allow to estimate concentration profiles with 5% accuracy [4]. In the case of curves depicted in Fig. 6, only for applied voltage of –1.5 V a monotonic dependence of resistance vs. carrier concentration was observed, but this relationship was not fully repeatable as observed for other measured samples, as presented earlier [5].

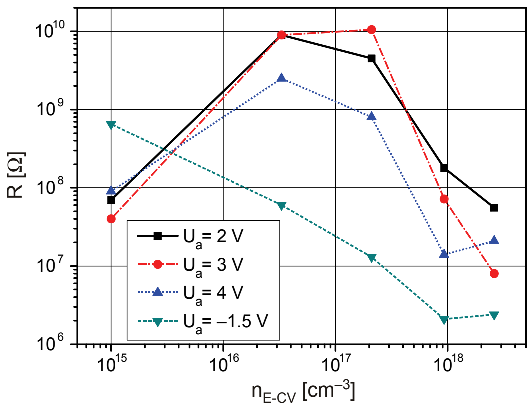


Fig. 6. Calibration curves of SSRM measurements for sample with short contact formed by AuGe/Ni/Au metallization.

The rectifying properties of AFM tip to GaAs contact could arise from various reasons: creation of Schottky potential barrier, surface traps occurrence or creation of diamond-GaAs heterojunction. In all of these cases, the limiting factor which determines the current flow is a potential barrier with specific height and width. There are two mechanisms describing the current flow through the potential barrier, tunneling and thermoemission. Based on the obtained *I–V* curves in reverse direction, it could be concluded that both current mechanisms could be present. Additionally, current flow mechanism could be different for low and highly *n*-doped gallium arsenide layers.

There exists another effect which so far has not been considered in the literature in context of SSRM measurement interpretation. It is a phenomenon of scaling the contact properties with potential barrier. This effect occurs for contacts with radius below about one micrometer, where one-dimensional simplified solution of Poisson equation is no longer valid. In that case, the thickness of the barrier is no longer determined only by the doping level or the free carrier concentration, but instead by the size and shape of the junction interface. In general, this could enhance the tunneling part of conduction mechanism through the potential barrier. Decrease in the potential barrier thickness caused by the reduction of the radius size of electrical contact is presented in Fig. 7. Based on our computation, in case of gallium arsenide for electron concentration of $1\times10^{16}$ $cm^{-3}$, the size effect started to play a significant role for the contacts size below 1 micrometer.

There could be evaluated the characteristic minimal value of an electrical contact radius ($r_{emin}$) below which the scaling effect of contact occurred. The dependence of $r_{emin}$ on carrier concentration for *n*-type GaAs was calculated on the basis of a simple model described in [6] and here presented in Fig. 8. Assuming that the typical radius of electrical contact of a doped diamond coated AFM tip used in presented measurements is about 30 nanometers, it could be estimated from Fig. 7 that for

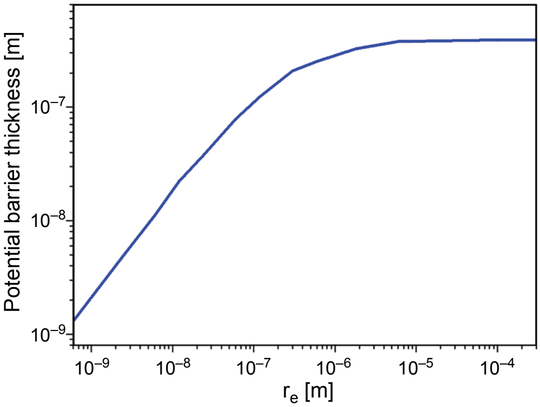


Fig. 7. Plot of the calculated potential barrier thickness as a function of contact size radius ($T = 300$ K, $\Phi_B = 0.7$ eV, $n = 1\times10^{16}$ cm$^{-3}$).

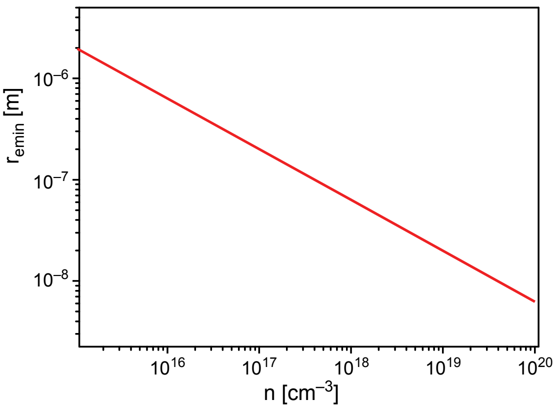


Fig. 8. Dependence of characteristic minimal radius of electrical contact on carrier concentration for GaAs ($T = 300$ K, $\Phi_B = 0.7$ eV).

layers where the carrier concentration was below $n = 4\times10^{18}$ cm$^{-3}$, the scaling effect influenced the potential barrier width and, in turn, influenced the electrical carriers transport through the contact created by the tip of an atomic force microscope.

In spite of many problems connected with the extraction of a quantitative result of SSRM measurement of GaAs layers, it is still possible to obtain two-dimensional qualitative images of AlGaAs/GaAs structures. The magnetic field sensitive field effect transistor was fabricated by MOVPE technology using the design of multi-layered heterostructure which cross-section is presented in Fig. 9**a**. The as grown and designed structures parameters accordance was confirmed by E-CV and photovoltaic spectroscopy measurements (presented in [7]). The spreading resistance profile of that structure is presented in Fig. 9**b**. In the obtained SSRM map, all layers with different

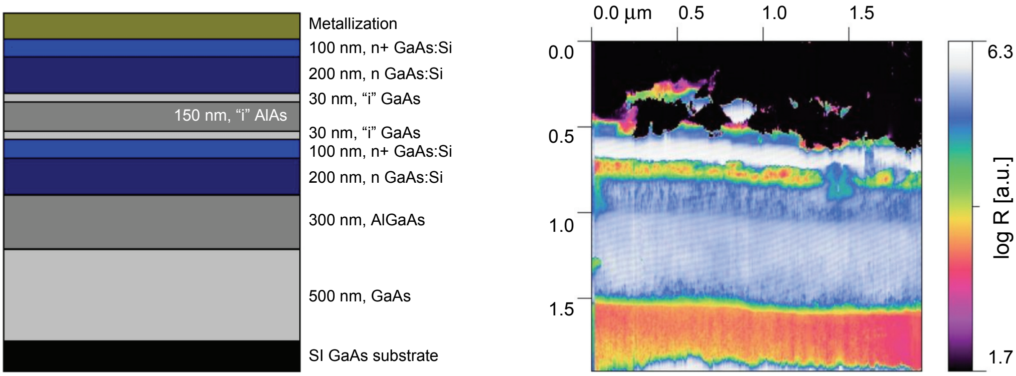


Fig. 9. Schematic cross-section (**a**) and SSRM image (**b**) of MAGFET structure.

composition and doping concentration could be recognized and the creation of an intermetallic phase in the region of contact metallization and top GaAs layer could also be observed. Such examination is very useful for defining optimal parameters of thermal formation of metal contact to thin GaAs layers.

## 4. Summary

It was presented that SSRM technique allows qualitative observation of carrier concentration in *n*-type gallium arsenide epitaxial layers. The optimal value of voltage applied to the tip during measurement has to be determined experimentally. The complicated mechanism of creating the AFM tip–semiconductor surface contact and the complex current transport mechanism, but also the scaling effect of the size of electrical contact on the potential barrier width preclude the quantitative characterization of GaAs layers.

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