Electrostatic force microscopy of Si- and GaAs- based device structures

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Scanning Kelvin Probe Microscopy (SKPM) and Electrostatic Force Microscopy (EFM) are the unprecedented tools for measuring the nanometer-scale variation of the contact potential (CP) between the tip and the sample surface [1]. The sensitivity of SKPM and EFM to CP variations is based on the linear dependence of the oscillating component of the electrostatic force on the CP value. The basic principles of the SKPM and EFM [1] permit to express this component (it is often called the force signal, the first harmonic H1, the main EFM signal) as:
$F_{el}(\omega) = (dC/dz)\times(V_{cp}(U_{bias})+U_{tip})\times U_{ac}\cos(\omega t) \sim H1$ (1),
where C is the tip/sample capacitance and an axe z is perpendicular to the sample surface; V_{cp} is the CP between the tip and the sample, that depends on the external dc bias U_{bias} applied to the sample; U_{ac} and U_{tip} are ac and dc components of the tip potential. In SKPM the absolute value of CP is measured by means of auxiliary feedback loop adjusting the main EFM signal magnitude to zero. One of the fruitful application of the SKPM from the practical point of view is the measurements of the potential distribution across the semiconductor device structure [2-4]. Most of semiconductor devices have layered structure. If the device is considered as homogenous in the layers plane, one may measure only the 1D potential distribution. In our report we show a simple way to precisely extract from the EFM data the CP profile in the absence of the auxiliary feedback loop. The obtained CP profiles match well with the measurements made by SKPM and also agree with the simulation results.

GaAs-based n^+-N-I-P-p^+ laser diodes and Si- based n^+-n-p-p^+ diodes are studied by the developed technique under applied forward biases. Two AFM systems, Autoprobe CP Research (Veeco) supplied only by EFM mode and Solver P47H (NTMDT) supplied by SKPM and EFM modes, are used for the cross-sectional measurements. The ac potential is applied to the probe tip made from heavily doped Si at frequencies around 100KHz and a voltage amplitude of 1V. The diodes are biased by an external constant voltage source.

Fig.1 illustrates the way of extracting the CP profile from the EFM data on the cleavage of the semiconductor laser diode structure. When obtaining a 2D image of the main EFM signal (Fig.1b), each next horizontal line of the image we increase a dc potential of the tip by a small step. In accordance to (1), the main EFM signal (H1) depends linearly on the tip potential as it is demonstrated by experimental data in the Fig.1e. The condition H1=0 determines the value V_{cp} of the CP at the position of cross-section $H1_b$ on the image in Fig.1b. Correspondingly, a 1D contour of CP may be found from the image on Fig.1b by adjustment the contrast of the image within a small diapason slightly above and below the zero level. As one can see (profile $H1_a$ across the layers of the structure in Fig.1d), the main EFM signal reflects the CP variation. Nevertheless, it can not be used for the precise analysis, since it does not give an absolute value of CP and, besides, depends on the tip-sample capacitance. The found absolute value of CP profile does not depend on the tip/sample capacitance and is displayed over the topography image (Fig.1a). Using the topography data and corresponding CP profile, we are now able to study the electrical junctions of the layered structures.

We have noted, however, that comparison of CP profiles, measured at the sample places with different morphology, may be conflicting. At the same time the difference between two CP profiles measured under some external bias and under equilibrium was not sensitive to the surface morphology. Therefore in the following we analyze such differences, that in fact determine the surface voltage drop. In Fig.2 the EFM study of another laser diode structure is presented. As one can see the main voltage drop takes place within an undoped I-region of the laser diode structure in agreement with the simple theoretical assumptions. At high operating current our data reveal an existence of the additional barrier at the calibration layer location. Detailed experimental data on the surface voltage drop profiles versus the current are shown in Fig.3a. Behavior of the bulk voltage drop was simulated theoretically. The results of such simulation shown in Fig.3b are in good agreement with the experiment.

We would like to underline the importance of the obtained results. Traditionally the improvement of the semiconductor device characteristics, e.g. decreasing of the extra serial resistance, is achieved by development of the contacts, whereas a voltage distribution across the device structure is not analyzed properly. The obtained EFM data attract the attention of the technologists to the transport properties of the auxiliary peripheral layers of the device structures. In case of laser diodes the observed parasitic voltage drop on these layers may cause a failure of the device. We have also performed a study of Si-based diodes that have strong deviation of the current voltage characteristics from the ideal behavior. Similar parasitic barrier for the injected carriers is observed at the first interface of the Si-diode.

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[1] M. Nonemacher, M.P.O'Boyle, H.K. Wickmarmasing, Appl.Phys.Lett. 58, 2091 (1991)
[2] F. Robin, H. Jacobs, O. Homan, A. Stemmer, et. al. Appl.Phys.Lett. 76, 2907 (2000)
[3] A. Ankudinov, A. Titkov, V. Evtikhiev, E. Kotelnikov, R. Laiho, et.al. PLDS, ¾, 9 (2001)
[4] A.V. Ankudinov, A.N. Tikov, et.al. Semiconductors, 35, 840 (2001)

Fig.1. Measurements of the CP profile by EFM in the absence of the auxiliary feedback loop. **a**-Topography and **b**-the main EFM signal images of the GaAlAs/GaAs based laser diode structure cleavage. P-contact bias is 1226 mV (I=50 A/cm^2), scan size is 5 µm^2 (512×512), the fast scan direction is along the horizontal axe x. Each horizontal line the tip bias increases by 1 mV from 100 mV (bottom) to 611 mV (top). See also the description in the text.

Fig.2. EFM study of the cleavage of the GaAlAs/GaAs based laser diode mesa structure under applied forward biases. The EFM data of the surface voltage drop are displayed over the gray scale topography image. Curves **1-3** were measured under the following biases on p-contact of the laser: 1- 513mV; **2**- 1075 mV (I=25 A/cm^2); **3**- 1735 mV (I=720 A/cm^2, lazing), the white arrow marks the peculiarity in the voltage drop profile related with the parasitic barrier.

Fig.3. Detailed EFM study of the parasitic barrier dependence on the injection current. **a**- experimental results of the surface voltage drop and corresponding topography cross-section of the parasitic barrier region, **b**- data of the bulk voltage drop obtained by the simulation of the part of the laser structure schematically presented as a bulk energy gap diagram.