Scanning Kelvin probe microscopy observation of the minority carriers escape from the active region of injection semiconductor laser diodes.

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In this contribution we focus on the investigation of nonequilibrium charge carriers escape into the emitters from the active region of operating semiconductor laser diodes. The carriers leakage processes have a strong influence on the laser efficiency and need to be accurately controlled. We present a new direct method, utilizing Scanning Kelvin probe microscopy (SKPM), for quantitative probing the minority carriers leakage processes.

It was earlier reported [1,2] that the distributions of the voltage applied to the semiconductor device might be probed by SKPM on its cleavages. There is a difference between the potential at the surface and the potential in the bulk of a semiconductor. That difference is the value of the subsurface band bending in semiconductor. If it is rigidly fixed, the voltage drop measured across the surface will reflect the real voltage drop through the device. In this work we test the validity of this assumption. In particular, it is shown that it can be used, when the state of the semiconductor device is close to the equilibrium or when the external biases applied to contacts of the device do not provoke a significant current flow. However, when the external biases give rise to injection of nonequilibrium carriers through the device, the experimental SKPM data may strongly deviate from the real voltage drop. We explain the last observation by the variations in the subsurface band bending due to nonequilibrium carriers capture on the surface states.

Two forward biased diode structures, a high voltage Si diode and a high power GaAlAs laser diode, are studied. The data of the potential distributions across the device surface are measured and the potential distributions through the device bulk are simulated. The difference of the external potentials emerging between the p^+- and n^+- regions bordering the p-n junction of

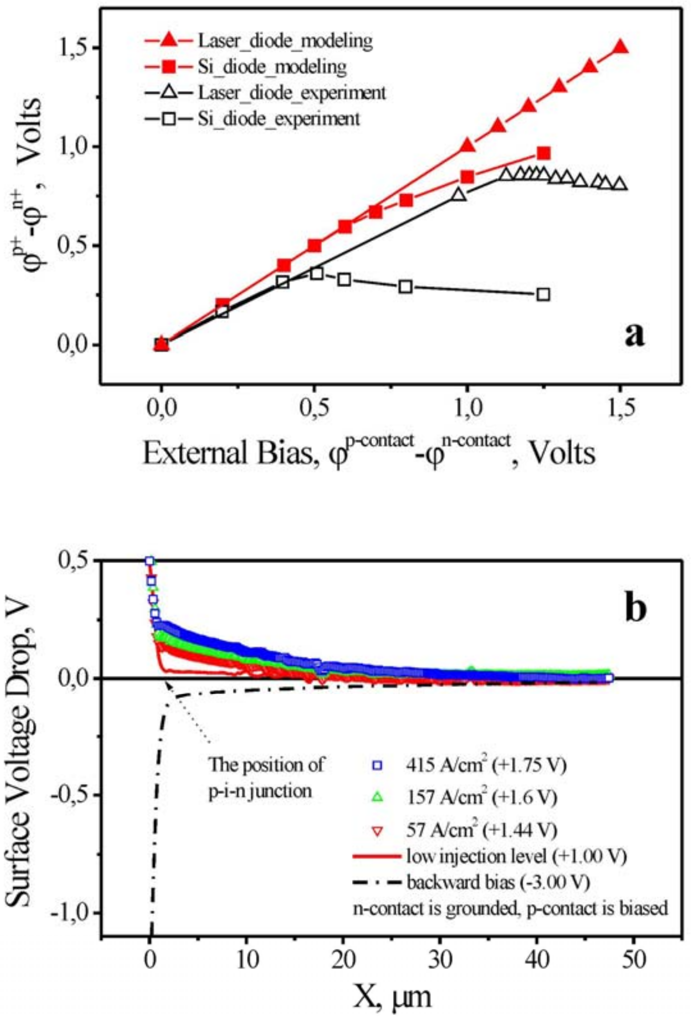

Fig.1. Comparison between simulation and experimental data- **a**; SKPM probing of the external potentials across n^+-GaAs surface on the cleaved mirror of high power GaAlAs/GaAs laser diode- **b**.

the device is analyzed in Fig.1a as a function of the applied bias. The experimental dependencies pass consequently through linear and nonlinear stages. When small biases applied, the p-n junctions of diodes stay closed, and both measured and simulated differences grow linearly. However, further increase of the applied biases accompanying by a detectable injection current through devices leads to evident discrepancies between measurements and modeling. Whereas the simulated dependencies show just insignificant nonlinearity, the experimental ones saturate and even decrease. The last trend is also manifested in an unexpectedly high potential drop observed along the surface of the grounded highly doped substrates. It is possible to agree the experiment with the simulation on the first stage, when the measured difference is linear and makes up about 80% of the applied bias. The small deviation of 20% can be explained by the SKPM instrumental broadening [3]. However the only instrumental broadening analysis does not permit to adequately treat the experimental dependencies on the second stage. The reason is the change of subsurface band bending, which value connects the potential at the surface and the potential in the bulk of semiconductor. In the following we present confirmations of the effect of nonequlibrium carriers injection in semiconductor device on the value of the subsurface band bending.

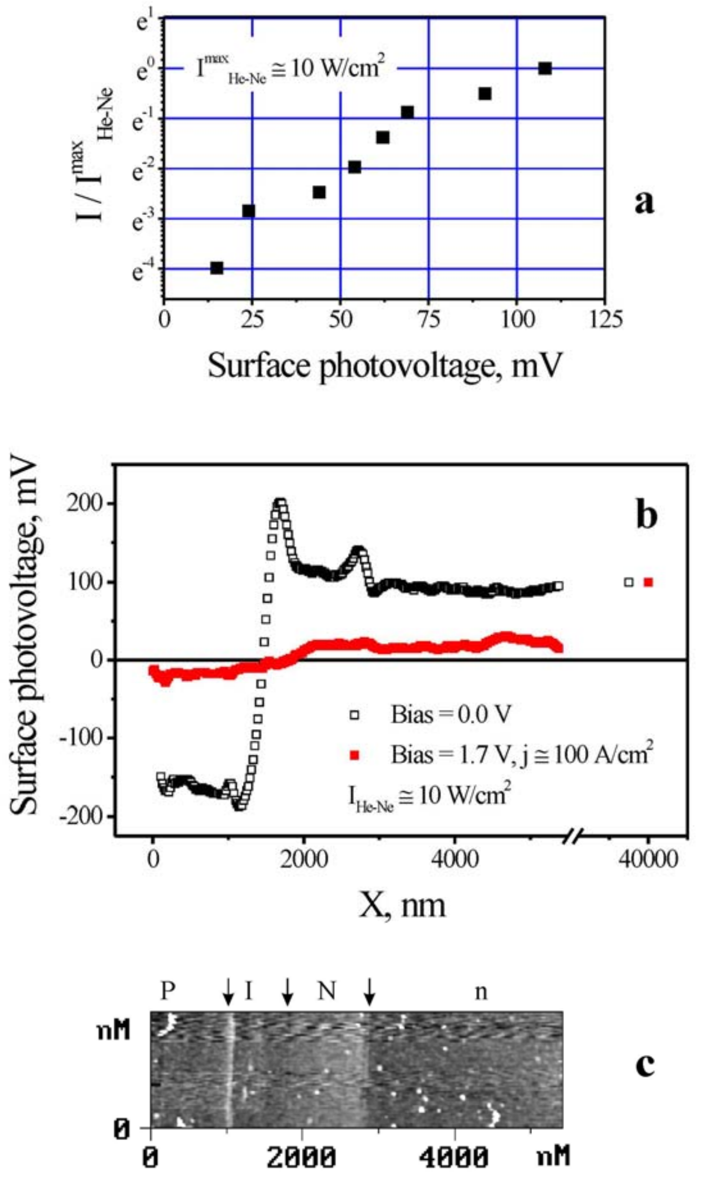

Fig.2. SKPM surface photovoltage study of the cleaved mirror of high power GaAlAs/GaAs laser diode. A dependence of the signal measured over n^+-GaAs surface on the light exctation power- **a**; SKPM signal distributions across the p-i-n junction area with applied to the device forward bias and without it- **b**; topography data- **c**.

On Fig.1b we present the potential drop dependencies at the length of several tens of microns along the surface of the grounded highly doped substrate of GaAlAs/GaAs laser for different applied biases. The shape of the dependencies measured for low injection level and for backward bias is explained in terms of SKPM instrumental broadening. Far from the p-n junction position, the signal magnitudes of both dependencies are proportional to the applied bias. In fact, the curve (+1.00 V) can be transformed to the curve (-3.00 V) by linear operations of sign inversion and multiplication by factor 3. With increasing the injection level, the situation changes and there appears a pronounced nonlinear dependence of the measured surface potentials on the applied bias. In this diapason of voltages and currents (slightly below and above the lazing threshold), the dependencies shift up in the vicinity of p-i-n junction approximately by 25 mV for every **e**-times increase in the current. The observed trend in the signal behavior is well attributed to the decreasing of the subsurface band bending on the device cleavage. Let us consider n-type substrate. The injection of the minority holes in the substrate results also in the holes current toward the surface. The holes current should be compensated by the electron current, the last being proportional to the $\mathbf{e}^{\Delta\Phi/\mathbf{k}T}$, where $\Delta\Phi$ is the decreasing of subsurface band banding and **k**T is 25 mV. What is important, the value $\Delta\Phi$ is determined by the amount of the escaping from the active region minority carriers that are captured on the surface states. Thus the measurements of $\Delta\Phi$ across the device surface permit to control the distribution of the injected minority carriers.

The manifestation of the minority carriers in the surface potential values is additionally confirmed in the local (beneath the tip end) surface photovoltage experiments. The value of surface photovoltage depends logarithmically on the light excitation power (and, hence, on the minority photocarriers density), its sign being positive for n-type and negative for p-type material [4]. Fig.2a shows the dependence of the SKPM surface photovoltage value on the light excitation power. The data were measured on the cleavage of laser diode over the n^+-GaAs substrate, forty microns away from the p-i-n junction both n- and p- contacts of the device are grounded. Using the grid on the graph in Fig.2a, one may measure that the local photovoltage value grows by approximately 25 mV for every **e**-times increase in the light intensity. Two profiles of the surface photovoltage data measured on the cleavage of a laser diode across the region with a p-i-n junction are shown in Fig.2b. The profile presented by open squares was measured without applied bias. As expected, the signal intersects the zero level approximately at the center of p-i-n junction. The signal levels over n- and p-part of laser are not the same. This is due to different density of surface photocurrent from both sides of p-i-n junction. The light illumination is homogeneous in space, but the photocurrent (and, hence, the photovoltage) depends also on the surface recombination rate, diffusion coefficients and lifetimes of carrier [4]. Therefore the photovoltage value can differ essentially for n- and p-type semiconductor. When a forward bias applied to the diode, the injected minority carriers appear at the opposite sides of the p-i-n junction. If the injection current is higher then the density of surface photocurrent, the value of surface photovoltage diminishes significantly. The very case is illustrated by the second profile in Fig.2b. Far from the p-i-n junction, when the density of injected minority carriers becomes small, both profiles have the same signal value. A known light excitation power in the SKPM surface photovoltage data allows to locally connect the potentials measured without photoexcitation, but with applied external bias, to the surface current density of minority carriers. This is used to calculate the total surface current of minority carriers leakage in operating semiconductor devices. Besides, the difference between experimental and simulated potentials presented in Fig.1a may be interpreted as a measure of the total surface current.

To summarize, the reported SKPM study presents an efficient experimental method for direct studies of the carriers leakage into emitters in semiconductor injection laser diodes and demonstrate a possibility for a numerical control of minority carriers densities.

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[1] P. Girard, Nanotechnology **12**, 485 (2001).
[2] A. V. Ankudinov, V. P. Evtikhiev, E. Yu. Kotelnikov, A. N. Titkov and R. Laiho, J. Appl. Phys. **93**, 432 (2003).
[3] F. Robin, H. Jacobs, O. Homan, A. Stemmer, W. Bachtold, Appl.Phys.Lett. **76**, 2907 (2000)
[4] R. Shikler, N. Fried, T. Meoded, and Y. Rosenwaks, Phys.Rev. B **61,** 11 041 (2000).