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MICROCRYSTALLINE, NANOCRYSTALLINE, POROUS, AND COMPOSITE SEMICONDUCTORS

Effect of the Interaction Conditions of the Probe of an Atomic-Force Microscope with the *n*-GaAs Surface on the Triboelectrization Phenomenon

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Abstract—Triboelectrization as a result of the scanning of an atomic-force-microscope probe over an *n*-GaAs surface in the contact mode is investigated. The dependences of the local potential variation on the scanning rate and the pressing force of the probe are obtained. The results are explained by point-defect formation in the surface layers of samples under the effect of deformation of these layers during probe scanning. The charge localized at these defects in the case of equilibrium changes the potential of surface, which is subject to triboelectrization. It is shown that, for qualitative explanation of the observed dependences, it is necessary to take into account both the generation and annihilation of defects in the region experiencing deformation.

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1. INTRODUCTION

The mechanical friction-accompanied interaction between solid surfaces during their relative motion leads to a wide spectrum of tribological phenomena [1–3]. In this case, the triboelectric effect related to a variation in the electric potential of a solid surface upon friction with the surface of another solid [4–8] is quite frequently observed. Notwithstanding the fact that the triboelectric effect has been known for a long time, its nature is still not entirely clear. Atomic-force microscopes (AFM) are a convenient tool for investigating triboelectrization effects. One of the reasons for this fact is the possibility of maintaining a constant speed of motion and pressing force of the probe to the surface provided by the AFM, which makes it possible to form a region of nanometer dimensions with identical deformation distribution under the probe at an arbitrary point on the sample surface for reasonably smooth surfaces. In addition, it is possible to determine the relative surface-potential variation for an area subject to deformation due to probe scanning in the same microscope with the help of scanning Kelvin-probe microscopy (SKPM) [9, 10].

The triboelectrization of an *n*-GaAs surface under its mechanical interaction with an AFM probe was investigated in [11]. It was established that, when scanning an individual portion of the epitaxial-film surface is realized in the contact or semi-contact modes, the potential of this surface varies by 3–8 mV. In this case, the scanning parameters were chosen so that no visible modification of the surface topography on this portion was observed. The main purpose of this study is the investigation of a local change in the *n*-GaAs surface potential at various speeds of motion and probe pressing force during the course of scanning in cases where a part of the surface-layer material is removed as a result of friction.

2. SAMPLES UNDER INVESTIGATION, CONDITIONS UPON TRIBOELECTRIZATION, AND INVESTIGATION TECHNIQUES

We investigated *n*-GaAs epitaxial layers 0.5 μm thick doped with Si at the level of 5×10^{17} cm^{-3} and grown on an *n*-GaAs (001) substrate by metal-organic chemical-vapor deposition (MOCVD). The surface of the samples was atomically smooth, which was confirmed by the AFM measurements. The contacts to the epitaxial film necessary for measuring the surface potential were formed by the electric-breakdown method.

To carry out triboelectrization of the sample surface and also to measure the topography and the surface-potential distribution, we used an MESP probe coated with a Co/Cr layer with a probe curvature radius of 35 nm [12]. Surface triboelectrization and the potential measurements were carried out under conditions of room temperature and a low relative humidity of 10–15% in the medium; for this purpose,

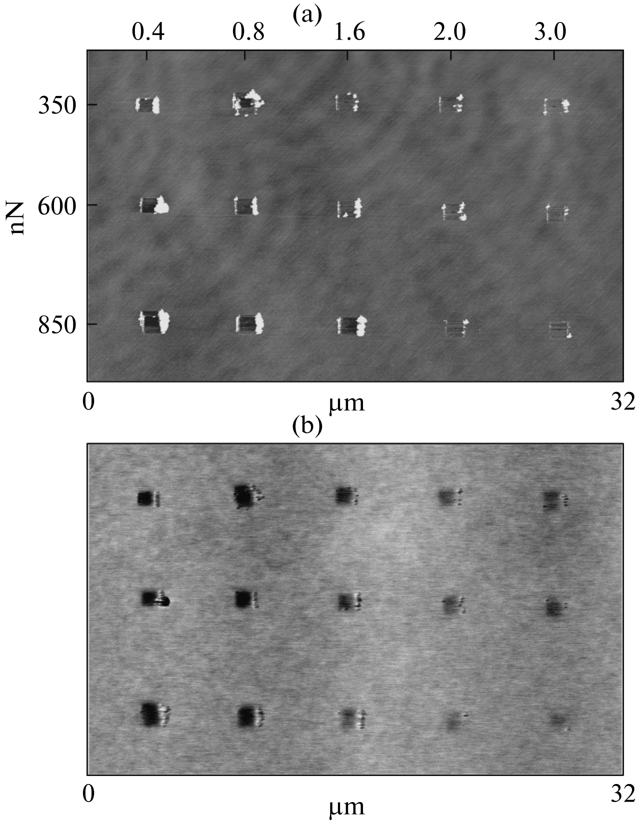

Fig. 1. AFM image of (a) the topography and (b) the potential of the *n*-GaAs surface, portions of which were subject to tribological modification at probe pressing forces *F* of = 350, 600, and 850 nN and scanning velocitiess *v* of = 0.4, 0.8, 1.6, 2.0, and 3.0 µm/s.

gaseous nitrogen was pumped through the microscope chamber.

Tribological modification of the surface was carried out by AFM scanning in the contact mode when the probe was in direct contact with the sample surface and moved along it with a set constant pressing force and speed. The scanning-area size amounted to 1 × 1 µm^2, and the number of lines was 512. The pressing force was determined taking into account the probe rigidity for each region, which amounted to approximately 5 N/m. The AFM-probe rigidity was determined from analysis of its amplitude–frequency spectrum of harmonic vibrations caused by the Brownian motion of air molecules [13].

When using the SKPM method for measurements, the probe-motion speed during the first passage, which determined the surface topography of the sample in the semi-contact mode, was chosen to be reasonably high so as to avoid the additional variation in the surface potential possible at low scanning velocities.

Since the modification occurred in the contact mode, the probe under use should be stable against mechanical interactions; at the same time, conducting probes are required for the SKPM method; therefore, we chose a probe coated with a Co/Cr layer. As showed the investigations with a scanning electron microscope, the probe curvature radius remained almost unchanged after repeated scanning of the sample.

3. RESULTS OF MEASUREMENTS

In Fig. 1, we show AFM images of the topography and the *n*-GaAs surface potential, a number of portions of which were subject to tribological modification at various probe pressing forces F and scanning velocities v. The topography-change depth was within the limits from 0.3 nm at $F = 350$ nN and $v = 3.0$ µm/s to 1.3 nm at $F = 850$ nN and $v = 0.4$ µm/s. The elevations observed at the edges of the modified regions in the direction of probe motion along the fast-scanning axis can be related to the removal of material from these regions and disregarded when determining the topography depth and the potential variation [4].

The profile of the potential U for different pressing forces and scanning velocities are shown in Fig. 2. The dependences of the potential variation in the modified region on the value of the reciprocal scanning velocity at different values of the probe pressing force are shown in Fig. 3. As can be seen from this figure, this dependence is characterized by a fast increase in the absolute value of this variation with decreasing v in the region of high velocities and the transition to saturation at low velocities.

4. DISCUSSION OF RESULTS

The value reciprocal to the scanning velocity is proportional to the residence time of a small modified-region area below the probe under conditions of rather large external deformation. On the other hand, in the model relating a small potential variation with a change in the number of surface states, the absolute value of the potential variation observed for *n*-GaAs, as shown in [11], is proportional to the surface concentration of introduced defects with an energy below the Fermi level on the surface. Therefore, the dependences $|\Delta U| = f(1/v)$ represent the change in the defect concentration on the residence time in the highly deformed state caused by the probe. Due to this, the features of the dependence $|\Delta U| = f(1/v)$ noted above in the model of the change in the number of surface states can be qualitatively explained taking into account also the annihilation of defects instead of only their deformation-stimulated generation in the stressed region. In fact, in the simplest case of the homogeneous distribution of strain in the modified bulk, the change in the defect concentration can be described by the equation

$$\frac{dn}{dt} = (N-n)\frac{1}{\tau_1} - n\frac{1}{\tau_2}, \qquad (1)$$

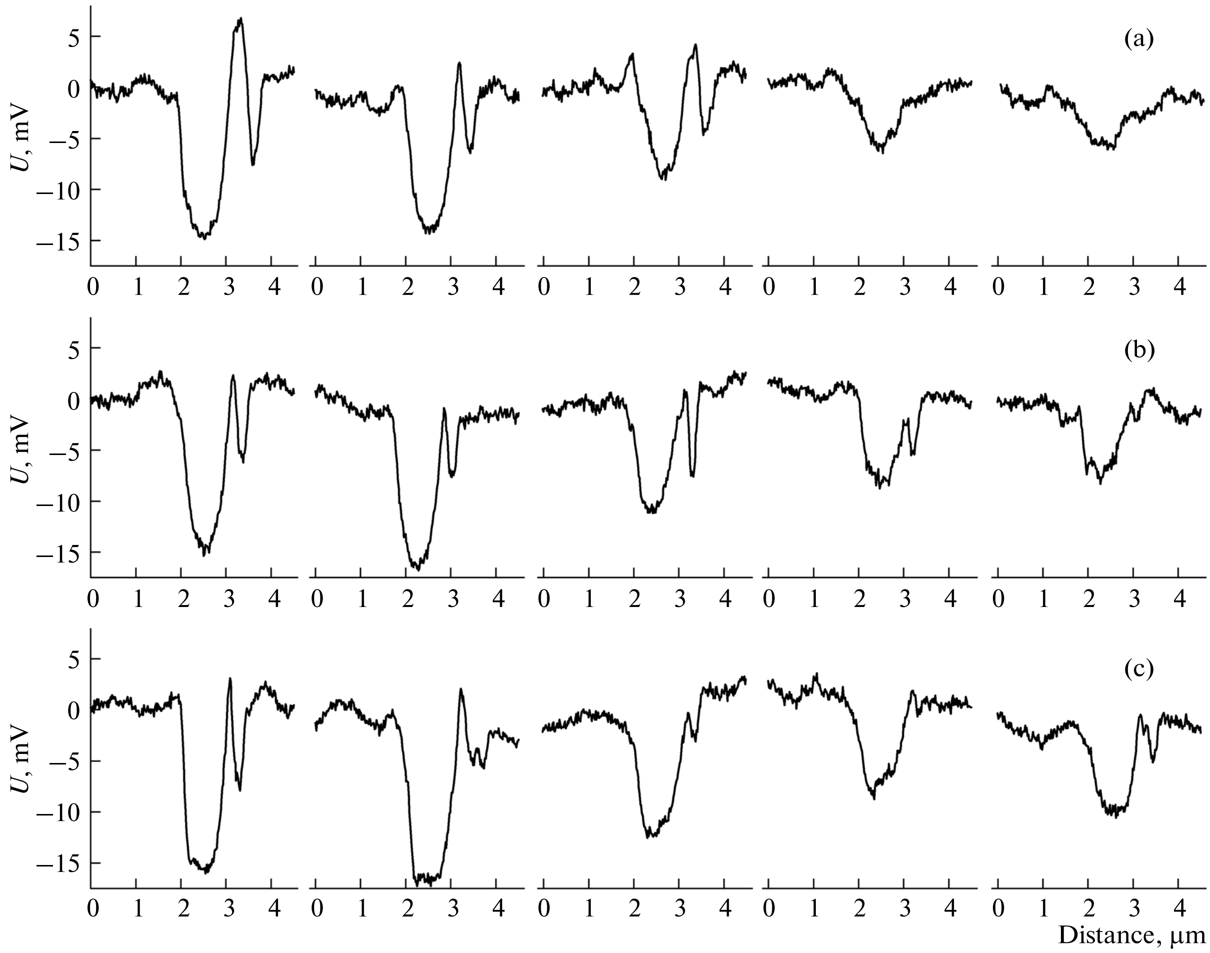

Fig. 2. Profiles of the potential U of the n-GaAs surface, portions of which were subject to tribological modification: (a) at the probe pressing force $F = 350$ nN and the scanning velocity $v = 0.4$, 0.8, 1.6, 2.0, and 3.0 μm/s; (b) at the probe pressing force $F = 600$ nN and the scanning velocity $v = 0.4$, 0.8, 1.6, 2.0, and 3.0 μm/s; (c) at the probe pressing force $F = 850$ nN and the scanning velocity $v = 0.4$, 0.8, 1.6, 2.0 and 3.0 μm/s.

where n is the concentration of introduced defects, N is the initial concentration of possible sites of defect formation, τ_1 is the characteristic generation time, and τ_2 is the characteristic annihilation time. The solution of this equation is

$$n(t) = \frac{Nt_0}{\tau_1}\left(1 - \exp\left(-\frac{t}{t_0}\right)\right), \quad t_0 = \frac{\tau_1\tau_2}{\tau_1 + \tau_2}. \qquad (2)$$

A similar form of the dependence $n(t)$ is seen also in the case of a constant defect-generation rate, i.e., when the value of n in the first term of Eq. (1) can be neglected in comparison with N. In this case, $\tau_1 \gg \tau_2$ and $t_0 = \tau_2$.

The approximation of experimental data by the expression

$$|\Delta U| = |\Delta U_0|\left(1 - \exp\left(-\frac{V_0}{V}\right)\right), \qquad (3)$$

which follows from Eq. (2), is shown in Fig. 3. Notwithstanding the fact that the model disregards the inhomogeneity of strain under the probe and the possibility of the generation of defects of different nature, expression (3) rather well describes the experimental dependences.

As can be seen from Fig. 3, the value of ΔU_0 increases only slightly with increasing probe pressing force more than twice (from 350 to 850 nN). This means that the number of defects in the surface layer remaining on the sample after rather long interaction with the probe depends only slightly on the pressing force. At the same time, the parameter v_0 related to the characteristic time t_0 of the defect generation–annihilation process appreciably increases with pressing force. This increase can be at least partially caused by an increase in the lateral size of the sample surface region experiencing strong deformation in which defect formation also occurs. As a result of this, the total time of the presence of each element of the surface layer under conditions of strong deformation

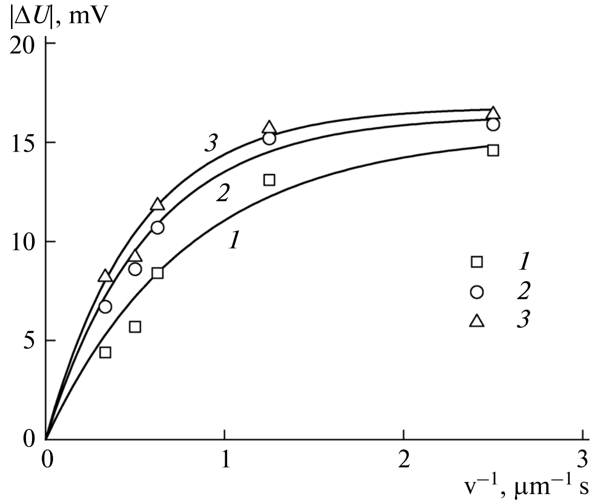

Fig. 3. Dependences of the variation ΔU in the potential of the modified n-GaAs surface on the value of the reciprocal scanning velocity for different values of the probe pressing force F = (*1*) 350, (*2*) 600, and (*3*) 850 nN. Points are experimental, the curves correspond to calculations in accordance with formula (3) at the following values of parameters $|\Delta U_0|$ = (*1*) 15.51, (*2*) 16.36, (*3*) 16.78 mV, and v_0 = (*1*) 1.25, (*2*) 1.75, and (*3*) 1.95 μm/s.

upon sample scanning increases, and the same density of defects is formed at a greater scanning velocity.

The obtained values of v_0 enable us to estimate the order of the characteristic time t_0. If l is the lateral size of the semiconductor region, which is subject to deformation during interaction with the probe sufficient for the formation of defects that lower the Fermi level on the surface, the total time Δt of the presence of each element of the surface layer under such a condition when scanning the sample is

$$\Delta t = \frac{l}{v}\frac{lk}{L}, \tag{4}$$

where L is the size of the scanning region along the vertical and k is the number of scanning lines. To estimate the smallest possible value of l, we can use the Hertz model, which gives an underestimated value of the contact radius [14]. As follows from this model, the contact-spot diameter amounted to $l_{\min} \approx 12$ nm for the probe pressing force $F = 600$ nN. Then, substituting $v = v_0 = 1.75$ μm/s, $L = 1$ μm, and $k = 512$ in Eq. (4), we obtain $\Delta t = t_{0\min} \approx 0.045$ s. On the other hand, an estimate of the contact-spot diameter from the measured depth of the scanning region (Fig. 1) yields a value of ~16 nm, and calculations based on the Hertz model show that the diameter of the region of relatively high strains at the applied pressing forces exceeds the contact-spot diameter by no more than 6 nm. From here it follows that $l_{\max} \approx 22$ nm and $t_{0\max} \approx$ 0.15 s. Thus, the value of t_0 is within the range from 0.04 to 0.15 s.

5. CONCLUSIONS

The dependences of the triboelectrization effect on the value of the reciprocal velocity of scanning the n-GaAs sample using the probe of an atomic-force microscope, which were investigated in this study at pressing forces up to 850 nN for a probe with the curvature radius of 35 nm, are characterized by an initial increase in the absolute value of the potential variation at high scanning velocities of (2–3 μm/s) and a subsequent transition to saturation of the effect at scanning velocities of 0.4–0.8 μm/s. The similar behavior of these dependences is explained in the model [11] relating the variation in the surface potential to the formation of intrinsic defects in the surface region [15–17] with energy levels below the Fermi level at the surface and requires that this model takes into account both the generation of such defects in the region with relatively high strain and their annihilation.

The ultimate surface concentration of defects formed at low scanning velocities can reach several units multiplied by 10^{10} cm^{-2} according to estimates similar to those made in [11]. We may assume that it is Ga vacancies, their complexes with donors, and antisite defects $\mathrm{Ga_{As}}$ or their complexes with other defects that can serve as such point defects. According to available publications, all these defects are acceptors, generate electron states with levels in the lower half of the band gap [18–21], and are negatively charged even near the surface of n-GaAs. Also, it was revealed [22] that, upon plastic deformation of the GaAs bulk, the concentration of defects containing $\mathrm{Ga_{As}}$ increases.

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