Triboelectric current generation by friction of conductive probe and GaAs surface

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Generation of triboelectric current during friction of a conducting probe against a GaAs surface with a layer of native oxide has been studied. It is shown that the triboelectric current in GaAs is two orders of magnitude higher than the current in Si and the direction of the current is determined by the difference in the work function between the probe and the GaAs surface. The increase in triboelectric current in GaAs compared to Si is due to the high density of surface states and the tunneling of electrons from the probe onto them during friction.

Keywords: GaAs, triboelectricity, triboelectric generation, surface states.

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When a conductive contact frictions against the surface of a semiconductor surface without external electrical voltage, an electric current flows in the circuit „movable electrode–substrate–external load“ [1]. This phenomenon is called triboelectric generation, which was previously demonstrated when the probe frictions against the surface of Si [2], GaAs [3], InP [4] and other semiconductor materials. The mechanism of triboelectric generation in semiconductor materials is controversial, and possible explanations include the tribovoltaic effect [5], tunneling of hot charge carriers through a natural surface oxide [6], flexoelectricity [7] and other models. For the practical application of triboelectric generators, it is necessary to maximize their efficiency and the achievable output power. One way to increase the output power is to increase the short circuit current. It was shown in a number of papers that increase in the density of surface states leads to a significant increase in the short-circuit current [2]. Since Si surface with a layer of natural oxide has a low density of surface states, the increase in surface roughness by etching and corresponding increase in the density of surface states resulted in increase in the current density by several orders of magnitude to the values $\sim 100\,\mathrm{kA/m^2}$. In $A^{\mathrm{III}}B^{\mathrm{V}}$ semiconductors the density of surface states is by several orders of magnitude higher than in Si, and high current densities were obtained by friction conducting probe with a tip radius of 100 nm on InP surface ($\sim 15\,\mathrm{kA/m^2}$) [4]. It is important to note that in GaAs under atmosphere conditions, due to faster oxidation of Ga, As layer is formed near the surface, at the oxide/GaAs interface. This layer formation leads to a high density of surface states, which can be both donor and acceptor [8]. Recently, an increase in the triboelectric current density in GaAs compared to Si was shown, and the same triboelectric current polarity was shown for *p*- and *n*-GaAs [3]. However, a number of controversial assumptions were made about the influence of charge carrier mobility on the efficiency of triboelectric generation (the higher the mobility is, the higher the triboelectric current is), and the influence of surface roughness on the micrometer scales in GaAs on the density of surface states. Indeed, the mobility of charge carriers in GaAs is higher than in Si, however, in *p*-GaAs the mobility is significantly lower than in *n*-GaAs, while in the paper [3] a higher triboelectric current is observed precisely in the *p*-type.

The purpose of this paper is to study the triboelectric generation during friction of the conducting probe on the surface *p*- and *n*-GaAs and to discuss possible mechanisms that determine its efficiency.

In paper the substrates *p*-GaAs (100) with doping level $10^{19}\,\mathrm{cm}^{-3}$ (100), *n*-GaAs (100) with doping level $10^{17}\,\mathrm{cm}^{-3}$ and *n*-GaAs (111)B with doping level $10^{18}\,\mathrm{cm}^{-3}$ were studied. Also for comparison the substrate *p*-Si (100) with doping level $10^{19}\,\mathrm{cm}^{-3}$ was used. All substrates had a native oxide layer on the surface with an average roughness level of 0.2 nm. Triboelectric generation studies were carried out using scanning probe microscopy (SPM) with NTegra AURA probe microscope (NT-MDT, Russia). Conductive probes HA_HR_DCP (NT-MDT) with a diamond-like coating and a tip curvature radius of 100 nm were used. The method for measuring short circuit current (I) when the probe frictions against the surface is presented in paper [4]. As a rule, a laser with a wavelength of 650 nm is used to detect the deflection of the cantilever (probe), which leads to parasitic illumination of the surface under study. To avoid this effect, the laser was turned off, but in this configuration, surface scanning with simultaneous current recording was carried out with open feedback. In this mode, scanning is performed in the plane XY (see Figure 1, a), while the plane of the substrate surface is usually inclined relative to the plane XY. In this configuration, the probe begins to touch the surface only in the area where these planes intersect. In

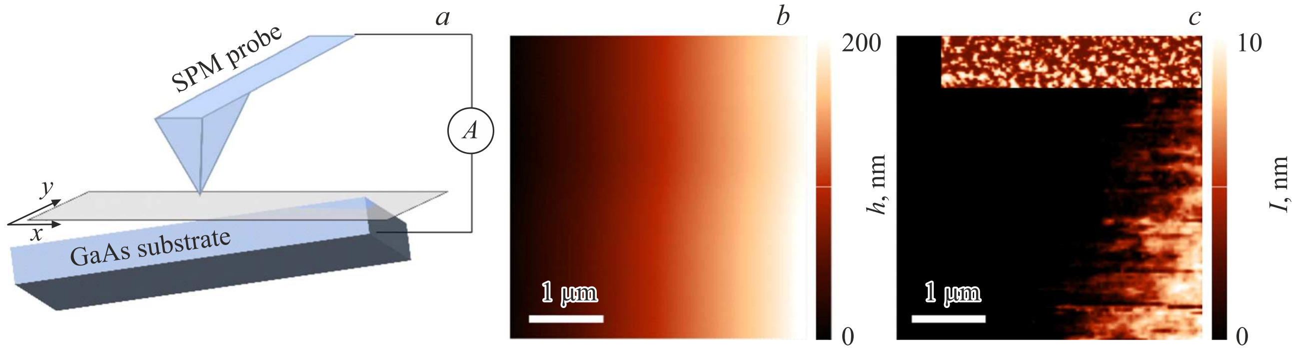

Figure 1. (a) Scheme of experiment to measure the triboelectric current during friction of SPM probe on the surface of semiconductor substrate n-GaAs (111). (b) Image of surface topography. (c) Map of short circuit current $I(x, y)$ that occurs when the probe frictions against the surface. The force of probe pressing to the surface from the middle of the scan to the right border increased from 0 to 3000 nN. The inset at the top of the Figure is a short-circuit current map of size 1000×200 nm, obtained when the probe contacts the surface at all scan points with a pressing force ~ 5000 nN.

Triboelectric current and surface potential of the substrates under study

Substrate	p-Si (100)	p-GaAs (100)	n-GaAs (100)	n-GaAs (111)
I, nA	−0.04	17	2	10
U, mV	−10	140	350	300

this case, the force of probe pressing to the surface increases monotonically. To determine the inclination of the substrate surface to the plane XY, scanning was preliminary carried out with feedback turned on; the corresponding topography image is presented in Figure 1, b. Figure 1, c shows a map of the short-circuit current $I(x, y)$ when scanning the n-GaAs (111) substrate with feedback turned off. From the map $I(x, y)$ it follows that when the probe frictions against the surface, the electric current emerges in the circuit. It is important to note that with increase in probe pressing to the surface, i.e. when moving to the bottom right corner of the image, the current value increases and reaches 10 nA. The increase in current with increase in pressing on the surface is probably due to increase in the probe-surface contact area. Experiments with a larger increase in pressure did not show current increasing (see insert in Figure 1, c), due to the saturation of the probe force acting on the surface caused by the finite stiffness of the cantilever. Also, experiments in which there was no lateral movement of the probe, but at the same time there was increase in pressure on the surface, did not show the emergence of the current.

Positive current values in the used setup correspond to a positive voltage applied to the substrate relative to the probe. To determine the mechanism responsible for the polarity of the triboelectric current, Kelvin probe microscopy study was performed. This method measures the surface potential (U), which is the difference between the work functions of the probe and the surface under study. In studies we used the probe that was used to measure the triboelectric current. The Table presents the maximum measured triboelectric current values for GaAs and Si substrates, as well as the corresponding surface potential values.

It follows from the Table that, indeed, the value of the triboelectric current in GaAs is by several orders of magnitude higher than in Si. Besides, the polarity of the triboelectric current correlates with the sign of the surface potential and does not correlate with the type of substrate doping. It is important to note that the current values obtained on polished substrates correspond to the values obtained on unpolished ones, and presented in the paper [3]. A possible explanation for the low current values on polished substrates in the paper [3] is that the authors used probes with Pt conductive coating, which quickly degrades at the probe tip during friction.

Let us discuss the reasons leading to increase in the triboelectric current in GaAs with layer of native oxide compared to Si. Possible reasons include increase in the density of surface states and mobility of charge carriers in GaAs compared to Si. However, the mobility of charge carriers in heavily-doped p-Si and p-GaAs is almost the same. The density of surface states in Si with layer of natural oxide is $10^{10}-10^{11}\,\mathrm{cm^{-2}\,eV^{-1}}$, in GaAs $10^{12}-10^{13}\,\mathrm{cm^{-2}\,eV^{-1}}$ [9]. The high density of surface states in GaAs is explained by more intense oxidation of Ga and the formation of layer of excess As on the surface of the semiconductor substrate. Pinning of the Fermi level on the states created by the As layer leads to the fact that the values of the surface potential in GaAs p- and n-types are close to each other (see Table) and their difference is significantly less than the band gap [8]. Figure 2 shows the band diagrams for GaAs with natural oxide layer for

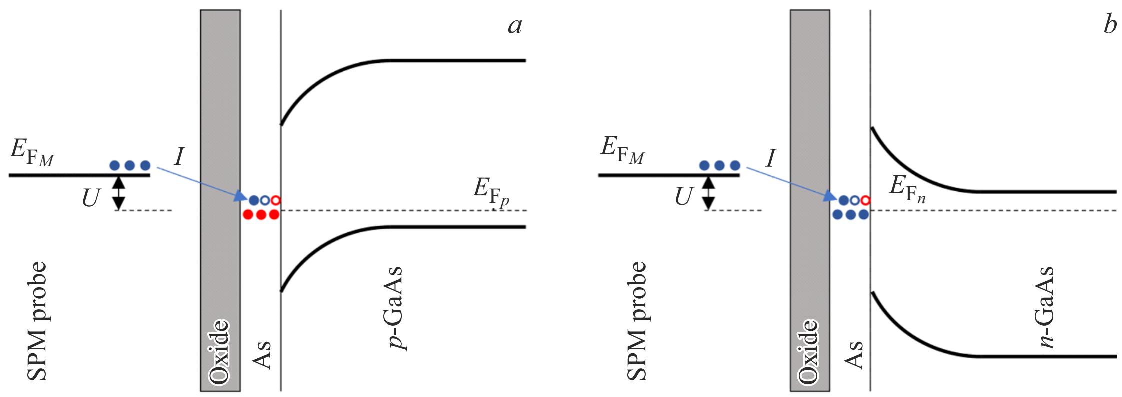

Figure 2. Band diagrams of the SPM probe and GaAs *a*) *p*-type, *b*) *n*-type. Blue filled circles indicate electrons, red filled circles represent holes. Open circles indicate the corresponding unfilled surface states.

p-GaAs (*a*) and *n*-GaAs (*b*). As a result of the Fermi level being pinned, the majority charge carriers move to surface states and a near-surface space charge region is formed. It is important to note that these surface states can trap both electrons and holes. Since the surface potential of *p*- and *n*-GaAs relative to the probe is positive, then without electrical contact the Fermi level of the probe is higher (see Figure 2). By creating electrical contact during friction, the Fermi levels of the probe and the surface will align, at that electrons will tunnel from the probe to surface states. The polarity of the observed triboelectric current for GaAs exactly corresponds to this configuration. The high density of surface states in GaAs compared to Si contributes to increase in the tunneling current through the surface oxide and increase in triboelectric generation. During scanning a continuous creation and destruction of a point contact occurs, accompanied by nonequilibrium processes of charge carriers tunneling to surface states from the probe with subsequent redistribution of charge carriers between bulk GaAs and surface states. Since tunneling increases with doping level, the sample with the highest doping level exhibits the highest triboelectric current [6].

Thus, the paper studied triboelectric generation during friction of a conducting SPM probe against GaAs surface with layer of native oxide. It was shown that the value of the triboelectric current in GaAs is by two orders of magnitude greater than the triboelectric current in Si. The polarity of the triboelectric current does not depend on the type of doping of GaAs and is determined by the difference between the work functions of the probe and the surface. The increase in triboelectric current in GaAs is due to the high density of surface amphoteric states caused by the layer of near-surface As and the electrons tunneling from the probe to these states during friction against the surface.

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Conflict of interest

The authors declare that they have no conflict of interest.

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