The Analysis of Nano-Size Inhomogeneities of Substrate by Surface Electrons over Superfluid Helium Film

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Abstract: The surface quality of the substrate is a crucial factor in building “clean” quantum-dimensional systems. There are a number of micro-nano metric methods for the analysis state of surface: the atomic force microscopy, the scanning tunneling microscopy and others. The SE (surface electron) over substrate has a “soft” hydrogen-like spectrum in the normal direction and the SEs mobility along is sensitive to the inhomogeneities of the substrate and this is analyzed in work. The values of electron mobility and energy of thermal activation are basic parameters of transport process which essentially depend on the helium film thickness. For analysis of nano-size inhomogeneities of substrate here we apply a new method providing a uniformity of the film thickness on substrate and fixing of measuring cell with supply wires. The plunger with electro-mechanic driver into a hermetic chamber is used for variation the helium level and consequently the film thickness. Considering values the conductivity and the variation of potential along surface is estimated the effective size of roughness from several nanometers (for non-saturated helium film) to 10^2 nm (for saturated film).

Key words: Liquid helium, surface electron, low-dimensional systems, nano-technology.

1. Introduction

Nowadays there are increasing attentions to the surface substrate quality as well as to methods of analyzing it. The boundary of different matters or their phases is the main source of various kinds of inhomogeneous distorted quantum-size structure and of the work of nano-electron devices [1]. The number of micrometric and spectroscopic methods for the analysis of nano-roughness is used such as atomic-force microscopy, scanning tunneling microscopy, phase-interference method, and X-ray structural analysis and others. The quality of interface can also be defined on the features of carriers transport near the border. By the sensitive “tool” here can serve the system of electrons over the helium layer covering the substrate—SEs (surface electrons). Helium is extra-pure substance and its isotopes with a controlled quantity are only impurities. Because surface electrons are situated in small potential well which formed by the weak charge image forces on one

hand and by large potential of border on the other hand, so they are located on a relatively large distance from the surface and weakly interact with the environment [2]. Modulation of the substrate properties can change the dimensionality of electron system up to zero-dimensional what is good expressed in the case of thin of helium film on substrate. Such SEs serve by models of quantum-size solid-state systems [3] and the parameters they are easy governed by fields and by radiation. So many contemporary works are directed to using either energy state of an electron over helium or its spin in building quantum bits for quantum computing [4-6].

However, in this work the diagnostic of interfaces by SEs is based on the analysis of electron transport depending on helium film thickness on the substrate. The conductivity data are connected with variations of potential by inhomogeneities induced [7].

2. The Measuring Method and Experimental Procedure

The measurement system and conductivity calculation are similar to those in Ref. [8].

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Sommer-Tanner method is applied where the measuring electrodes capacitively binded with SEs [9]. Taking into account the cell geometric factor and the saturated value of the electron density, n , is determined the mobility [8-10]. The measuring cell is shown in Fig. 1, schematically. On measurement electrodes 1-2 with dimensions $15.6 \times 9.2 \text{ mm}^2$ are placed the dielectric substrate 3. Electrodes 1-2 are maintained at ground potential and to the electrode 6 applied negative potential $V_{\perp}$. Negative potential of guard ring 5 has magnitude $|V_g| > |V_{\perp}|$ and this provides the electronic spot on substrate with sharp boundaries. Although the thickness of the saturated film is not strongly dependent from distance between helium and substrate, H , namely as function $H^{1/3}$ [10] in determining nano-roughness can be significant errors without substrate leveling. It can be noted that the one-dimensional SE-system is more sensitive to inhomogeneities because electrons are localized normally to surface as well as transverse the channel additionally [7, 11, 12]. Earlier the film thickness on substrate was set by admitting some liquid helium to the chamber. In Ref. [10] the film was formed by bellows system with helium. In Ref. [13] it used apparatus for research and made analysis of nano-roughness. The device comprises both helium chamber and the measuring cell arranged horizontally over helium. The vertical motions of cell with use of electromechanical system lead to changing of film thickness. Despite the originality of mechanism the uniform film on substrate is absent like in previous cases. The capacity of connecting wires here changes too. All these circumstances lead to the errors in the measurements.

In this work for roughness definition a new variant of the device is proposed (Fig. 2, schematically presented). The device has auto-horizon of cell by the plummet method. The variation of helium level is produced by displacement of plunger in chamber with helium providing here immobility of wires. The apparatus is comprised of helium chamber 3, the hinge

1 and the plumb 2, which situated on opposite ends of vertically oriented cylinder 6. On upper end of cylinder mounted a measuring cell 4 the center which is connected by the hinge 1 with the support frame 5. At the bottom of the cylinder 6 mounted immobile coil 9 with coaxially moving coil 8 connected with the plunger 7. Horizon of substrate up to 0.5 mrad is set using the laser beam reflected from the substrate to the screen when the cell turned around. The coils are wound by the superconducting NbTi wire for heating

Fig. 1 The measuring cell. Here 1-2—the measurement electrodes, 3—dielectric substrate, 4—helium film, 5—guard electrode, 6—upper electrode, 7—heat filament.

Fig. 2 The device analysis of substrate nano-inhomogeneities. Here are 1—the hinge, 2—plumb, 3—helium chamber, 4—measuring cell, 5—support frame, 6—cylinder, 7—plunger, 8—movable coil, 9—immobile coil, 10—bottom of helium chamber.

minimization. The operation of device is next. The chamber is filled with liquid helium to the top plunger surface (or slightly higher its). At given potential upper electrodes of the cell are emitted electrons from source onto the helium film covering substrate. At given current of coils the plunger moves to top some distance displacing the liquid helium down. Changing of H changes the film thickness on substrate. It is noted that the immobile coil may be replaced by the permanent magnet with corresponding geometry.

3. Analysis of Inhomogeneities and Discussion

The energy spectrum of SE is a hydrogen-like $E_n = Q_d^2 R / n^2$ (here Q_d is the effective force of the electron image in the dielectric, R is Rydberg's constant and n is natural numbers) with energy of the ground state a few meV for helium substrate. The mobility (conductivity) of surface electrons above helium is limited when they interact with helium atoms in a pair and with ripplons—quantized vibrations of the helium surface. The electron mobility at the holding field $E_\perp$ is $\mu_r = 8 \cdot \sigma \cdot \hbar / m \cdot e \cdot E_\perp^2$ (here e and m are charge and mass of a free electron, respectively and σ is the surface tension of helium). With inhomogeneities on the substrate the effective mobility of SE is determined as $\mu^{-1} = \mu_s^{-1} + \mu_{in}^{-1}$ (here μ_s and μ_{in} are surface electron motilities without and with inhomogeneities on the substrate, respectively). Inhomogeneities of interface induce the variations of potential described as [12]

$$\delta V \approx -Q_d \frac{e^2}{4\pi\epsilon_0 Z} \frac{\pi\xi}{A} \left(\frac{A}{Z}\right)^{1/2} e^{-\frac{2\pi Z}{A}} \quad (1)$$

where, ϵ_0 is the dielectric permittivity of vacuum and value Z is electron distance to the substrate; ξ and A are the effective amplitude and period of the inhomogeneities, respectively. Following estimations like Ref. [7] at $Z \sim 10^{-5}$ - 10^{-6} cm the SE transport is insensitive practically to the nano-roughness however

the value δV is more than 10^{-3} K at $Z \sim A / 2$ which is essential. Value of $\delta V \sim 1$ K, leads to a significant reduction in SE conductivity. The film thickness of superfluid helium is determined as $d = d_0 / H^{1/3}$ ($d_0 = 288 \text{ nm}^{4/3}$ is constant determined by the van der Waals potential) for thin films. The roughness of the sample surface substantially affects the electron conductivity as observed in Refs. [10, 13-14] and theoretically described in Ref. [15]. The thermo-activated mechanism of carrying the effective conductivity is $\sigma^* = \sigma_0 e^{-\Delta/T}$ (here σ_0 is the electron conductivity for the clean substrate and Δ is thermo-activation energy).

The assumption of what value of Δ corresponds to δV can calculate the value A from Eq. (1). In view of the quantum uncertainty relations it can be additionally estimated the effective relaxation time of the carriers and its mobility correspondingly. The value of Δ can be determined with good approximation from the temperature dependence of SE-conductivity in ripplon-scattering region like in Ref. [16].

The “dip” effect can take place in a number of cases at coinciding film thickness with a lateral size of roughness and gives additional information about irregularities.

Fragment substrate (AFM picture) of the glass as an example is presented in Fig. 3. The values of the effective amplitude of roughness and of the lateral size are estimated about 10 nm and 40 nm, respectively.

Fig. 4 reflects the dependence of SE mobility vs. thickness of helium film on sital substrate [14]. The mean size of the roughness surface, R_z is less 32 nm (the technical specifications).

One can see (Fig. 4) a substantial increase of the mobility with film thickness. Some features of SE in mobility are observed at $d \sim 30$ nm. The conductivity as function of film thickness gives us judgment about the substrate surface quality on nanometer scale, which coincides with estimates on Eq. (1).

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Fig. 3 AFM fragment the substrate surface with inhomogeneities (a); the nano-scans (b).

Fig. 4 The SE-mobility vs. thickness of helium film covering glass substrate.

4. Conclusion

Here we considered the non-destructive method of analyzing the quality of substrate surfaces by measuring SE conductivity changes above a helium film at changing its thickness. The connection between variations of potential substrate at a given film thickness with an effective size roughness of

interface is shown.

Analyzing SE conductivity on the given film vs. the thermal activation energy of the carriers and considering the threshold conduction can define the roughness dimensions with good accuracy. It is shown apparatus for realization of method determining the quality of substrate surface. The apparatus comprises moving by driver a plunger in cylinder suspended to supporting frame at upper part and the weight from below cylinder. Features of the device are next: auto-horizon of the cell with substrate by the method of plumb; the variation of level difference between the surfaces of the substrate and helium by moving plunger; the exclude here moving wires of cell at varying the liquid level. This method allows identifying the nano-roughness size from few nm to 10^2 nm.

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