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Point-Contact Spectroscopy of Mo/Si Superlattices

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Investigations of multilayer structures based on superconducting and semiconductor films have recently gained particular interest due to the search for topological superconductors. The nature of the unexpected increase in the critical temperature in such superlattices is still a matter of debate. Possible sources include the unusual mechanism of Cooper pairing in such superstructures, the appearance of superconductivity in semiconductor layers, or amorphization of the interface region between two dissimilar films. In this work, we have studied Mo/Si nanolayer superlattices with the superconducting transition temperature between 7 and 8 K which were prepared by RF magnetron sputtering. Mesoscopic point contacts on them have been realized by bringing a sharp metallic tip of silver in touch with the sample surface. Using Andreev reflection spectroscopy for extracting the value of the superconducting order parameter, we have performed point-contact measurements of the Mo/Si superlattices spectra well fitted with the Blonder-Tinkham-Klapwijk theory that assumes conventional *s*-wave ordering in the superconducting state. Our results show that the surprisingly high temperature of the normal-to-superconducting state transition in the Mo/Si superlattice is not related to any exotic mechanism but is rather connected with the formation of an amorphous alloy at the interfaces between Mo and Si layers. We believe that the main factor leading to the enhancement of superconducting characteristics is the emergence of soft vibrational modes in disordered Mo/Si interlayers and, as a result, the appearance of the so-called bosonic peak in the phonon spectra of the superlattices. The results obtained are expected to stimulate efforts for realizing silicon-based superconductive devices with far-reaching application potential, in particular, in superconducting electronics.

Keywords: Mo/Si superlattices, Point-contact spectroscopy, Superconducting energy gap, Amorphous interlayers.

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1. INTRODUCTION

One or two-dimensional realization of topological superconductivity is nowadays a very topical problem. Most of proposed implementation schemes comprises superconductor/semiconductor heterostructures [1, 2], including corresponding superlattices [3]. For this reason, it seems appropriate to return to the question of the nature of superconductivity in multilayer periodic structures formed by conventional superconductors and semiconductors. Such investigations, which were very active in the last decades of the 20th century, did not lead to a generally accepted conclusion about the origin of the increase in critical superconducting parameters in the superlattices compared to single layers of the same superconducting material. Undoubtedly, the first superlattices that require careful study are those that are based on the most popular semiconductors, silicon and germanium. At the same time, it should be taken into account that the remarkable properties of multilayers are ascribed to atomistic and electronic structures of the interfaces, the crystallinity of the substrate, the formation of alloying phases due to interdiffusion as well as the two-dimensional nature of the layers themselves.

In this paper, we focus our attention on the molybdenum-silicon system, which has the highest critical temperature T_c among Mo-based superlattices. Since a bulk sample of *bcc* Mo is a poor superconductor with $T_c = 915$ mK [4], and the cubic phase of Si manifests superconductivity only under extreme conditions (very low temperatures, extremely high pressures and heavy doping beyond the solubility limit [5]), the rise in T_c should be attributed to the multilayer nature. At the same time, theoretical investigations suggest emergence of superconductivity in doped elemental semiconductors like silicon and germanium under certain conditions [6, 7] and recently, a superconducting phase with a high critical temperature above 10 K and an average superconducting energy gap of 2 meV was indeed found in moderately doped crystalline silicon samples under non-superconducting metallic point contacts [8]. Since silicon is nowadays the most ubiquitously used material in electronics, the latter finding stimulated us to perform point-contact study of Mo/Si

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superlattices using conventional Andreev reflection spectroscopy for extracting the values of superconducting order parameters in Mo layers forming the Mo/Si superlattices.

2. EXPERIMENT

The samples with 30 Mo/Si bilayers were prepared by RF magnetron sputtering. The Mo and Si films of the thicknesses of 5.0 nm and 2.5 nm respectively were alternately deposited onto Al-oxide substrates previously cleaned by sputter etching. Mesoscopic point contacts on the Mo/Si superlattices studied were made by bringing a sharp metallic tip of silver in touch with the sample surface. The superconducting transition temperatures T_c between 7 and 8 K were found using the conventional four-terminal approach. In Fig. 1 we demonstrate a temperature behavior of the Mo/Si superlattice resistance in the region of a normal-to-superconducting state transition. At temperatures above T_c, the resistance is sufficiently high, due to which it was possible to realize the transport regime without significant tip pressure on the studied Mo/Si superlattice samples.

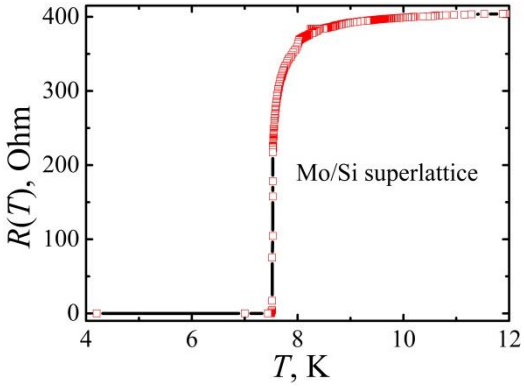

Fig. 1 – Resistance versus temperature dependence of the Mo/Si superlattice exhibiting the normal-to-superconducting state transition

Differential conductance $dI(V)/dV$ versus V spectra of two representative point contacts measured at the liquid-helium temperature $T = 4.2$ K is shown in Fig. 2. The current in such devices is controlled by transport channels with the highest transmission probability (that is why the point-contact transparency reaches values of the order of unity). If so, then an electron (hole) incident on the point-contact interface from the normal tip at energies less than the superconducting energy gap Δ of the superlattice forms a Cooper pair in the superconducting Mo/Si multilayer and reflects back as a hole (electron) with opposite spin and group velocity to the incident one. This quantum process is called *Andreev reflection*. It is clear that such an effect results in the enhancement of the in-gap differential conductance $G(V) = dI(V)/dV$, the derivative of the current I across the point contact with respect to the voltage bias V applied to it, approaching for $V >> \Delta/e$ the normal-state value $G_N = 1/R_N$ where R_N is the normal-state resistance of the junction. To calculate the normalized $G(V)R_N$ spectrum for an arbitrary interface transparency we apply the Blonder-Tinkham-Klapwijk (BTK) model that assumes ballistic and one-dimensional character of the electron transport through a contact of N and S metals. Within the model, possible elastic scattering at the contact interface is described by the parameter $Z = U_0 / (\hbar v_F)$, where $U_0\delta(x)$ is the localized effective potential and v_F is the Fermi velocity, while effective inelastic scattering inside the superconductor is characterized by the Dynes parameter Γ. With increasing Z, the shape of the $G(V)$ curve for the junction formed a normal tip and a superconductor studied changes from a flat section at $|V| < \Delta/e$ to peaks at $V = \Delta/e$. Fig. 2 demonstrates good agreement between conductance spectra measured for the Mo/Si superlattice with that calculated using the BTK model. Note that the energy gap Δ values, which varied from 1.0 to 1.3 meV, well agree with the literature data, see, for example, related publications [9, 10].

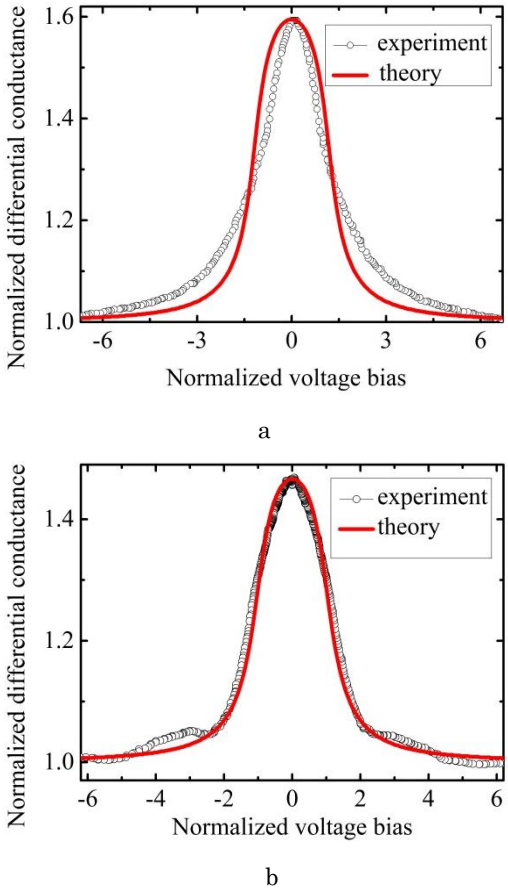

Fig. 2 – Comparison of the measured normalized conductance spectra $G(V)R_N$ versus normalized voltage bias eV/Δ for two representative point contacts formed by a silver tip and a Mo/Si superlattice and the expected theoretical curves for the following fitting parameters: (a) $\Delta = 1.05$ meV, $Z = 0.02$ meV, $\Gamma = 0.28$ meV, $R_N = 7.1$ Ohm; (b) $\Delta = 1.18$ meV, $Z = 0.11$ meV, $\Gamma = 0.28$ meV, $R_N = 17.2$ Ohm, the measurement temperature $T = 4.2$ K

3. RESULTS AND DISCUSSION

Let us transfer to the discussion. Several scenarios have been proposed for explaining the origin of the strong superconductivity enhancement in Mo/Si multilayers: (i) lattice distortion caused by the mismatch

between lattice parameters of the layers, (ii) intermixing or interdiffusion within their interfaces and formation of an amorphous region, (iii) novel superconductivity mechanisms as, for example, excitonic one [11]. Detailed experiments [11] brought some arguments in support of the idea that the superconductivity of Mo/Si multilayers results from an amorphous MoSi layer formed in the interfacial region with a thickness of about 3 nm. It was argued [11] that the superconducting properties of the superlattices are controlled by the interplay of three components: amorphous MoSi alloy, crystalline Mo, and amorphous Si.

Our experiments indeed support the latter statement since they demonstrate good agreement with the BTK theory based on the conventional concept of superconductivity in metals, thus rejecting the hypothesis of exotic superconductivity in superconductor/semiconductor superlattices. Secondly, the energy gaps, the ratios of which to the critical temperature slightly exceed the value of 3.52 predicted by the conventional theory. Most likely, this means that a superconducting state with an increased T_c takes place at the interfaces between molybdenum and silicon, and the energy gap observed by us is the corresponding gap in the molybdenum film, increased compared to its free state due to proximity to the nearby interface.

Concluding, the point-contact spectra of Mo/Si superlattices can be fitted well with the BTK theory that assumes conventional *s*-wave ordering in the superconducting state. In contrast to the observation of a surprisingly high temperature superconducting phase in semiconducting silicon [8], our results show that the growth of T_c in the Mo/Si superlattice is not related with any exotic mechanism but rather is connected with the formation of an amorphous alloy at the interfaces between Mo and Si layers. At a certain frequency range, amorphous materials exhibit excess of soft vibrational modes comparing to crystals, known as a 'boson peak' [12, 13]. Typically, superconductivity in amorphous materials is strongly coupled, with the electron-phonon coupling parameter $\lambda > 1$. The presence of the boson peak means the need to transit from the oversimplified model of weak-coupling pairing to the Eliashberg theory of strong-coupling phonon-mediated superconductivity [14, 15].

The authors of the paper [16] used a Lorentzian form to model the phonon spectral density

$$B(\omega,k) = \frac{\omega\Gamma(k)}{\pi\left\{\left[\omega^2 - \Omega^2(k)\right]^2 + \omega^2\Gamma^2(k)\right\}}, \qquad (1)$$

following from the Green function form

$$G_\lambda(\omega,k) = \frac{1}{\omega^2 - \Omega_\lambda^2(k) + i\omega\Gamma_\lambda(k)}, \qquad (2)$$

that takes into account propagating and diffusive damping (due to disorder-induced scattering) terms given by $\Omega_\lambda^2 = \upsilon_\lambda^2 k^2$ and $\Gamma_\lambda(k) = D_\lambda k^2$. Here υ_λ and D_λ are the speed of phonon propagation and the diffusion constant of the λ phonon branch, respectively. The subscript λ in (2) refers to either longitudinal $\lambda = L$ or transverse $\lambda = L$ displacement fields, the diffusive form D_λ of the damping follows from related simulations performed over a broad range of k. The authors of Ref. [16] found a non-monotonic dependence of the electron-phonon coupling parameter λ upon the disorder characteristic D with a maximum as a function of disorder, which monotonically grows upon increasing the speed of sound. Such tendency may be ascribed to two competing factors. On the one hand, the Lorentzian vibrational peak becomes bigger, which makes more phonon states accessible for pairing at low ω. On the other hand, upon increasing D further, the Lorentzian becomes broader and eventually shallower due to the term $\sim D^2$ in the denominator of the Lorentzian (1). These two opposite tendencies cause the presence of a peak in the dependence of the electron-phonon coupling constant λ on the diffusivity D, the position of which shifts towards higher diffusion coefficients as the transverse speed of sound in a given material increases.

The presence of a maximum in the λ-vs-D dependence means that the disorder effect on the main superconducting characteristics of a particular metal is controlled by its position on the λ-vs-D curve in the original crystalline state. If the initial superconductor has a relatively small value λ, then the disordering could enhance the electron-phonon coupling strength and we may observe the growth of T_c, as it happens, for example, in aluminum [16]. We believe that the same statement is true for molybdenum. In addition to being important for further understanding of nanoscale superconductivity in superconductor/semiconductor superlattices, the above results are expected to stimulate efforts for realizing silicon-based superconductive devices with far-reaching application potential, in particular, in superconducting electronics [17, 18].

ACKNOWLEDGEMENTS

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Точково-контактна спектроскопія Mo/Si надґраток

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Останнім часом у зв'язку з пошуком топологічних надпровідників особливий інтерес викликають дослідження багатошарових структур на основі надпровідних і напівпровідникових плівок. Природа неочікуваного підвищення критичної температури в таких надґратках досі є предметом дискусій. Можливі джерела – це незвичайний механізм куперівського спаровування в надструктурах, поява надпровідності в напівпровідникових шарах або аморфізація області розділу між двома різними плівками. У роботі ми досліджували наношарові Mo/Si надґратки з температурою надпровідного переходу між 7 і 8 К, які було виготовлено методом радіочастотного магнетронного розпилення. Мезоскопічні точкові контакти на них були реалізовані шляхом дотику гострого металевого вістря зі срібла до поверхні зразка. Використовуючи спектроскопію методом андреєвського відбиття для визначення величини параметра надпровідного порядку, ми виміряли точково-контактні спектри надґраток Mo/Si, які добре відповідали теорії Блондера-Тінкхама-Клапвійка, що передбачає звичайне *s*-хвильове впорядкування в надпровідному стані. Наші результати показують, що надзвичайно висока температура переходу з нормального в надпровідний стан у Mo/Si надґратці не пов'язана з якимось екзотичним механізмом, а скоріше є наслідком утворення аморфного сплаву на межі розділу між шарами Mo та Si. Ми вважаємо, що основним фактором, який призводить до посилення надпровідних характеристик, є поява м'яких коливальних мод у невпорядкованих прошарках Mo/Si і, як наслідок, виникнення так званого бозонного піку у фононних спектрах надґраток. Очікується, що отримані результати стимулюватимуть зусилля щодо реалізації надпровідних пристроїв на основі кремнію з далекосяжним потенціалом застосування, зокрема, у надпровідній електроніці.

Ключові слова: Mo/Si надґратки, Точково-контактна спектроскопія, Надпровідна енергетична щілина, Аморфні прошарки.