Oscillations of energy gap of superconducting vanadium–carbon sandwiches[1)]

M. B. Tsetlin and M. N. Mikheeva

(Submitted 2 January 1978)
Pis'ma Zh. Eksp. Teor. Fiz. 27, No. 3, 190–194 (5 February 1978)

Tunnel spectroscopy was used to measure the energy gap of superconducting vanadium–carbon sandwiches. It turned out that the gap oscillates in phase with the critical temperature and, furthermore, there are grounds for assuming that the ratio $2\Delta/kT_{cr}$ behaves in similar fashion.

PACS numbers: 74.50.+r, 74.70.Rv

The oscillations of the critical temperature in complex thin-film systems was observed already in many cases.[1,2] There exists also a theoretical model[3] that shows how such oscillations can arise, but this question is not yet completely clear. It is shown in[1] that in vanadium–carbon sandwiches a number of other parameters vary simultaneously with T_{cr}. To understand the gist of the phenomenon, it is of considerable interest to investigate the behavior of the energy gap in such systems and to compare it with the behavior of previously measured quantities.

The sandwiches were prepared in the same manner as in[1] in the form of a five-layer C–V–C–V–C, structure deposited on a pyroceram substrate (see insert of Fig. 1). The two vanadium layers were 100 Å thick, and the upper and lower carbon layers were 15 Å thick for all the samples. The thickness d_c of the inner carbon layer varied from sample to sample. The error in the determination of the thickness of each layer

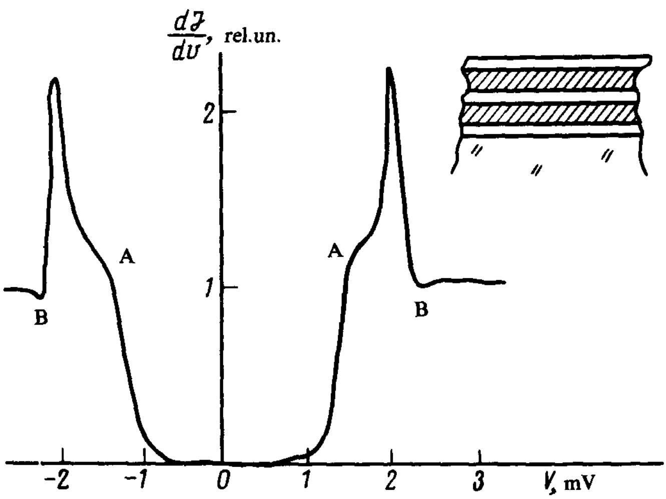

FIG. 1. Typical characteristics of C–V–C–V–Pb tunnel junctions. Insert: schematic section through the investigated C–V–C–V–C structure. The vanadium layers are shaded.

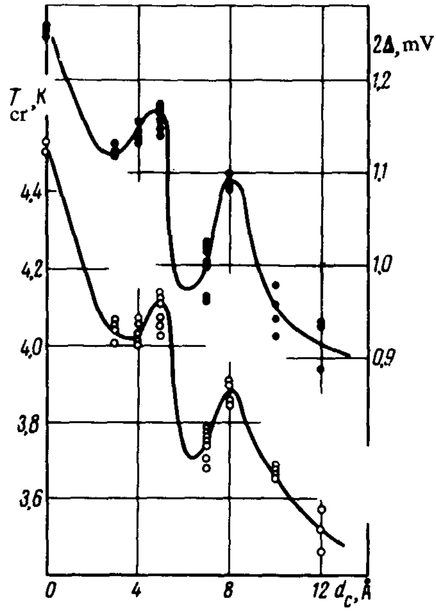

FIG. 2. Dependence of the energy gap of the sandwiches and of their critical temperature on the thickness of the internal carbon layer.

did not exceed 5%. All the samples were prepared in a single sputtering experiment, and the preparation and measurement of the tunnel junctions lasted about two months. A check has shown that neither the critical temperature nor the magnitude of the gap changed within that time. A simple and reliable technology of tunnel junction production was developed. It consisted of removing the substrates with the sputtered multilayer structure from the apparatus, etching on each sample a narrow track on which transverse lead strips were subsequently evaporated. The characteristics of four junctions were plotted simultaneously. As a rule two or three of them, and frequently all four, were suitable for the determination of the size of the gap. The areas of these junctions ranged from 0.003 to 0.2 mm^2, the resistivity ranged from 0.04 to 10Ω-mm, and the ratio of the Ohmic resistance at helium temperature ranged from 1.4 to 7. The characteristics were measured by the standard modulation technique, with a modulation amplitude 10 μV. Figure 1 shows a typical dependence of the differential conductivity on the voltage applied to the junction. The sharp peak at the voltages $v_{1,2}=\pm(\Delta_{Pb}+\Delta)$, where Δ is the energy gap of the investigated sample and the low conductivity $\sigma(0)$ at $v=0$, attest to the good quality of the junctions; the distance between conductivity peaks v_1-v_2 was determined accurate to 20 μV, and $\sigma(0)$ amounted to 0.5–3% of the Ohmic conductivity for the different junctions. We defined the doubled value of the gap 2Δ as $(v_1-v_2)-2\Delta_{Pb}$. and chose for lead the value $2\Delta_{Pb}=2.8$ mV. This value, which agrees with the accepted published one, was obtained by us earlier in measurements of Al-Pb junctions. The temperature 1.15 K at which the measurements were performed was separated by approximately 0.3 degrees from the critical temperature of the samples. At this temperature, the gap differs from $\Delta(0)$ by only 0.3%, and we have neglected this difference. It should be noted that the characteristics of the junctions, their good quality notwithstanding, differ noticeably from the classical values. This is attested by the singularities marked in Fig. 1 by the

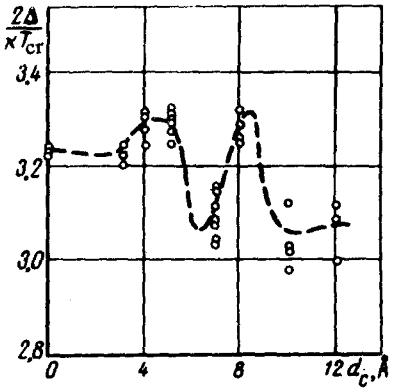

FIG. 3. Dependence of the ratio $2\Delta/kT_{cr}$ on the thickness of the internal carbon layer.

letters A and B, and also by the fact that the ratio $2\Delta/kT_{cr} < 3.52$, the value given by the BCS theory. As shown by our experiments with pure vanadium films, these singularities on the characteristics, as well as the decreased value of the gap determined from the tunnel measurements, are a general property of tunnel junctions based on vanadium. This is reported also by Yanson and Rybal'chenko,[4] who attributed the observed anomalies to the influence of the vanadium surface layers adjacent to the tunnel contact and having properties that differ apparently greatly from the properties of the metal in the interior of the film.

In our experimental setup, when the conditions on the surface were constants for all the samples, their influence reduces apparently to a systematic error in the absolute value of the gap and does not distort the general form of the sought $2\Delta(d_c)$ dependence. For each junction, in the same experiment in which we plotted the tunnel characteristics, we measured by a resistive method the critical temperature. Thus, Fig. 2, which shows plots of $T_{cr}(d_c)$ and $2\Delta(d_c)$, each junction corresponds to a point on either plot. The error in the determination of T_{cr}, which consists of the measurement error, the calibration error, and the error due to the width of the superconducting transition, did not exceed 1.5%, while the error in 2Δ amounted to 2%. The $2\Delta(d_c)$ and $T_{cr}(d_c)$ curves on Fig. 2 were drawn through the mean values of 2Δ and T_{cr} for each value of d_c. They show that both the critical temperature and size of the gap oscillate, although they do not yield information on the exact positions of the extrema. The oscillations of T_{cr} coincide with those described in[1]. It is seen from Fig. 2 that the size of the gap varies in phase with T_{cr}, while the amplitude of the variations is of the same order. The scatter of the points on the $T_{cr}(d_c)$ plot is apparently due to the inhomogeneity of the properties of the sample in different sections, as is also manifest by the scatter of the points for $2\Delta(d_c)$ where, in addition, a contribution is made also by the random variation of the conditions on the surface. It should be noted that the scatter of the points for both T_{cr} and 2Δ greatly exceeds the measurement errors, but is much smaller than the amplitude of the oscillations. Great interest, as is well known, attaches to the ratio $2\Delta/kT_{cr}$. This ratio was calculated for each junction, and this yielded the points on Fig. 3, which shows a plot of $2\Delta/kT_{cr}(d_c)$. The dashed line was drawn through the mean values of $2\Delta/kT_{cr}$, and shows that this quantity varies in nonmonotonic fashion in phase with 2Δ and T_{cr}, but the amplitude of the changes is smaller and is comparable both with the error of $2\Delta/kT_{cr}$ and with the scatter of the points. We are therefore unable to state with assurance that the oscillations of $2\Delta/kT_{cr}$ exist, although our results give grounds for such an assumption.

The authors thank V.M. Golyakov for supplying the samples, N.A. Chernoplekov for interest in the work, and I.K. Yanson and V.S. Egorov for useful discussions.

[1)]It is known that starting with a thickness of 1000 Å and higher, the carbon in films prepared by the method described in[1] is a synthetic diamond (see[1]). Since there are no data on the state of carbon in thinner layers, however, we shall use the term "carbon film."

[1]M.N. Mikheyeva, V.M. Golyanov, A.A. Teplov, and M.B. Tsetlin, J. Low Temp. Phys. **28**, 29 (1977).
[2]K.A. Osipov, A.F. Orlov, V.P. Dmitriev, and A.K. Milaĭ, Fiz. Tverd. Tela (Leningrad) **19**, 2226 (1977) [Sov. Phys. Solid State **19**, 1304 (1977)].
[3]Yu. Kagan and L.B. Dubovskiĭ, Zh. Eksp. Teor. Fiz. **72**, 646 (1977) [Sov. Phys. JETP **45**, 339 (1977)].
[4]I.K. Yanson and L.F. Rybal'chenko, Fiz. Nizk. Temp. **3**, 44 (1977) [Sov. J. Low Temp. Phys. **3**, 21 (1977)].