Tunneling and neutron scattering experiments on $A15$ V_3Si

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Tunnel junctions on $A15$ V_3Si with artificial tunnel barriers of aluminum oxide have been prepared by magnetron sputtering. The best samples showed $T_c = 14.0$ K and $\Delta_0 = 2.0$ meV. Detailed studies of the second derivatives revealed fine structures at the energies 11.0, 17.5, 21.5, 27.7, 32.5, and 39.5 meV. The location of these fine structures is in good agreement with the main features of the phonon density of states of V_3Si, which has been measured by inelastic neutron scattering experiments. The reduced density of states was strongly deformed, obviously due to the existence of a proximity layer between the V_3Si and the tunnel barrier. Using the proximity analysis for the best junctions, we found a satisfactory agreement of the fitted curves with the measured data.

INTRODUCTION

The first tunneling results on $A15$ V_3Si were published by Moore, Zubeck, Rowell, and Beasley[1] in 1979. They used silicon oxide as a tunnel barrier and studied T_c, Δ_0, and $2\Delta_0/k_B T_c$ as functions of the composition. Phonon-induced effects in the reduced density of states have not been published so far, presumably as a result of problems associated with the tunnel barrier. Encouraged by the success with Al and Al/Zr oxide barriers on Nb,[2] Nb_3Ge,[3] Nb_3Sn,[4] and Nb_3Al,[5] we tried to produce tunnel junctions on V_3Si with artificial barriers of Al oxide. Tunneling into the $A15$ compound V_3Si is of special interest because of its high T_c, and because it has been studied intensively in experiment and theory.[1,6–12]

EXPERIMENT

The V_3Si films were prepared by magnetron sputtering on hot (1100 °C) sapphire substrates. After cooling down to 200 °C, a thin Al layer was deposited *in situ* on the $A15$ film. The oxidation was performed at room temperature in ambient air for 15 min, resulting in junctions with resistances of about 2000 Ω. Pb counterelectrodes were evaporated to complete the junctions. The $A15$ structure of the V_3Si has been confirmed by x-ray measurements. First- and second-derivative measurements were taken on the junctions in the normal and superconducting state to generate a smooth reduced density of states (RDOS), which contained all the measurable fine structure. From the RDOS, the Eliashberg function α^2F was calculated using the McMillan-Rowell program, with proximity correction as proposed by Wolf *et al.* (PMMR).[13]

The neutron time-of-flight measurements were performed on the rotating crystal spectrometer IN4 at the high-flux reactor at Grenoble. The spectra were recorded in the energy-loss mode with an incident energy of 60 meV and at 28 different angular positions between 20° and 158° at 296, 77,[14] and 4.2 K.[6] The data were collected on polycrystalline material of the compound, with a T_c of 16.9 K, inductively measured. The results were converted into the two-dimensional scattering law $S(q,\omega)$, after corrections for background contributions, absorptions, and scattering losses on the flight path, sample, and container, and by taking account of the number of scattering centers in the sample and of the incident flux. The generalized phonon density of states $G(\hbar\omega)$ was derived from the scattering law by the extrapolation method of Eglestaff. In this procedure a zeroth approximation of $G(\hbar\omega)$ is calculated from $S(0,\omega)$. Thereupon, a scattering law is deduced taking into account all relevant multiphonon contributions. By comparison of the theoretical scattering law with the experimental one, the extrapolation is improved by iterative methods. As the ratio σ/M is almost identical for the two components vanadium and silicon, this generalized density of states is very close to the true density of states $F(\hbar\omega)$.

RESULTS AND DISCUSSION

The best thin film of our tunneling study had the following characteristic properties: $\Delta_0 = 2.0$ meV, $T_c = 14$ K (determined by the observation of the opening of the energy gap), and $2\Delta_0/k_B T_c = 3.3$. The I-V curve of the best tunnel junction (Fig. 1) shows a very small leakage at voltages below the lead gap (1.37 meV), but a comparably high excess current reaching about 20% of the total tunnel current. This excess current is most conveniently interpreted to be due to tunneling into a low-gap phase present at the film surface. Figure 2 shows a dV/dI trace, with the lead counterelectrode in the superconducting state. The slowly varying background of this curve indicates a high barrier height of our aluminum oxide layer. The big peaks near ± 8 and ± 12 mV are the resonance structures of the lead phonons, and the small step at ± 43 mV is caused by the vibrations of the silicon atoms in V_3Si. The sharp peaks just above the minima at the sum of the gaps of the V_3Si, and the lead film (arrows) reflect the knee structure often observed in tunnel junctions that are affected by proximity effects. In Fig. 3 the derivative of the reduced density of states (DRDS) is shown. This curve shows peaks at those energies where the Eliashberg function has peaks and shoulders. For our V_3Si samples, the trace indicates structures of this kind to be located at the energies 11.0, 17.5, 21.5, 27.7, 32.5, and 39.5 meV, as shown by the arrows.

The solid line in Fig. 4 shows the measured reduced density of states. The depression of the RDOS below zero at

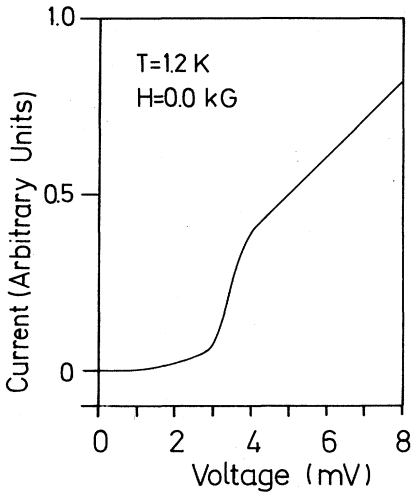

FIG. 1. I-V curve of a V_3Si-Al_2O_3-Pb tunnel junction measured at 1.2 K with zero magnetic field.

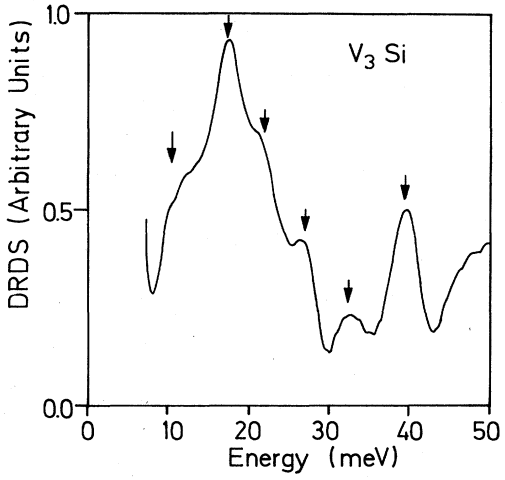

FIG. 3. Derivative of the reduced density of states. The trace shows structures (arrows) at 11.0, 17.5, 21.5, 27.7, 32.5, and 39.5 meV.

low energies is usually interpreted as an indication of the presence of a proximity layer between the tunnel barrier and the superconductor. The strong proximity deformation of the RDOS has prevented us from finding hints for the presence of deformations of another kind, which have been measured on Nb_3Sn by Schneider, Geerk, and Rietschel.[4] They found special effects in the RDOS, which were interpreted to be due to the influence of a strongly structured electronic density of states (EDOS) near the Fermi level. The deformations were found to decrease with decreasing T_c. For V_3Si, such an influence can also be expected.[15–17] But as our thin films are depressed in T_c, compared with the maximum T_c of V_3Si of about 17 K, we believe that the deformations due to the proximity effects are far stronger and of the greatest concern in correction procedure. As a result of the proximity inversion procedure, we get $d/l = 0.42$ and $2d/h v_F^* = 0.017$ for the proximity parameters (d is the thickness of the proximity layer, l the mean free path in the film which causes the proximity effect, and v_F^* the reduced Fermi velocity in this material). These values can be compared with junctions with natural oxide on niobium,[2] which give $d/l = 0.1$–0.2, and to junctions on Nb-Zr alloys,[18] prepared by the aluminum overlayer technique, where d/l was 0.43. With the above parameters, the PMMR inversion analysis yields an acceptable fit (dashed line in Fig. 4) to the measured data.

For the electron-phonon coupling constant λ, we get the value 2.21, and for the Coulomb pseudopotential, $\mu^* = 1.3$. This very high μ^* is surprising, and we are unable to offer a satisfying explanation for it. Possibly, the proximity model

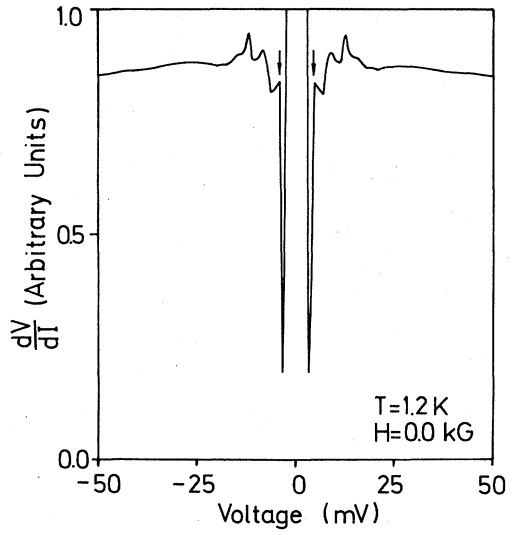

FIG. 2. First derivative of the junction of Fig. 1, with V_3Si and Pb in the superconducting state. The peaks marked by the arrows are due to a proximity layer between the V_3Si and the tunnel barrier.

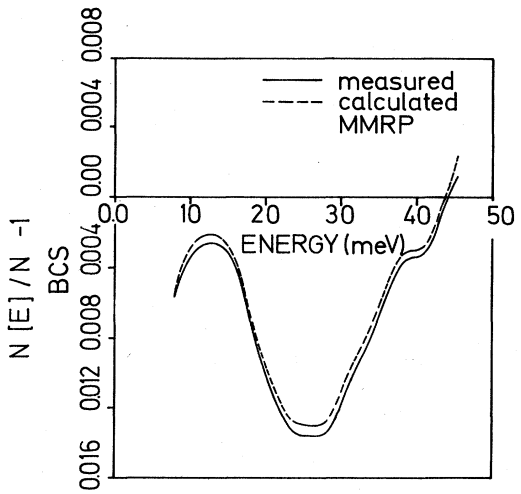

FIG. 4. The solid line shows the measured reduced density of states. The dashed line is a fit using the McMillan-Rowell proximity-inversion program ($d/ = 0.42$ and $2d/h v_F^* = 0.017$).

of Arnold and Wolf cannot describe our junctions in a quantitative correct way, as the authors used a very simple model for the depth dependence of the pair potential. So far, we do not have enough experience in PMMR analyses of junctions affected by such a strong proximity effect. From the work of Wolf and Noer[18] we know that they have used this model to examine Nb-Zr junctions with a comparably high value for d/l. But, unfortunately, there are no results published on Nb-Zr junctions with much better quality. Studies from Geerk, Gurvitch, McWhan, and Rowell,[2] who have measured junctions on Nb thin films with increasing thickness of the proximity layer, have not shown a dependence of μ^* on the junction quality at least for d/l ranging from 0.0–0.14. From this we cannot exclude the possibility that the very high value of μ^* on V_3Si from our analysis is partly due to a failure on the PMMR inversion procedure.

For V_3Si, indications for a strong influence of spin fluctuations (SF) have been reported in various publications.[12,19,20] If treated inadequately in terms of the usual superconducting parameters, SF depress T_c via an increase of the Coulomb pseudopotential μ^*.[21]

In Fig. 5 we shown the resulting Eliashberg function, the generalized density of states from neutron-scattering experiments and, in addition, an $\alpha^2_{tr}F$ function resulting from far-infrared absorption measurements by McKnight, Perkowitz, Tanner, and Testardi.[22]

Comparing $G(\hbar\omega)$ and α^2F, we find good agreement of the peaks and shoulders with respect to their energetic position. The peak near 40 meV, which mainly contains contributions of silicon vibrations, is smaller in α^2F than in $G(\hbar\omega)$. This shows that the phonons of that energy region couple weakly to the electron system. The weak coupling of the nontransition metal was also found in Nb_3Al by Geerk and Bangert.[5] In contrast to that the Eliashberg function below 25 meV is stronger in intensity than $G(\hbar\omega)$. This suggests that the electron-phonon coupling of the phonons contributing to this shoulder in $G(\hbar\omega)$ is comparably high. The strong coupling of the low-energy phonons was also found in Nb_3Sn (Ref. 4) and in Nb_3Al (Ref. 5).

McKnight *et al.*[22] have determined their $\alpha^2_{tr}F$ function using very thin V_3Si films with a T_c between 15 and 16 K. To generate this trace, they have fixed a peak at 42 meV and then varied the parameters of two Lorentzian oscillators to get an optimum fit to the measured absorption data. The discrepancies of their $\alpha_{tr}F$ function to the phonon density of states, which are the position of the 20 meV peak and the existence of an additional low-energy peak near 6 meV, have been explained by Mitrović and Perkowitz[17] by effects of a nonconstant EDOS near the Fermi edge. These effects, included in the analysis of the far-infrared data, resulted in an $\alpha_{tr}F$ function identical in shape to the phonon density of states. Our α^2F function determined in the tunneling experiment shows a similar shift to lower energies of the main peak near 22 meV with respect to the phonon density of states. Including the effects of a nonconstant EDOS in the analysis of the tunnel data, we expect that the peak would not shift to higher energies, but would lead to a further pronouncement of the low-energy phonons in the α^2F function. This has been shown by Schneider *et al.*[4] and Schneider,[23] for the case of Nb_3Sn. Therefore, we believe that the shift to lower energies of the 20 meV peak in $\alpha^2_{tr}F$ is a physical reality and that the influences of EDOS effects

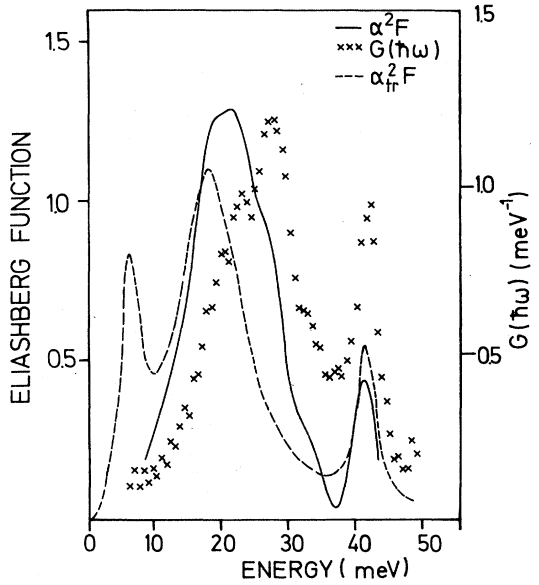

FIG. 5. The Eliashberg function (solid line) calculated from the tunneling experiment, the generalized density of states $G(\hbar\omega)$ (crosses) resulting from neutron scattering experiments, and the $\alpha^2_{tr}F$ (dashed line, arbitrary units) from far-infrared absorption measurements (Ref. 22).

on the analysis of the far-infrared data may have been overestimated by Mitrovic and Perkowitz.[7] As we outlined above, this may be caused by the depressed T_c of the samples. Structures in the tunneling α^2F, which could verify the 6 meV peak in $\alpha^2_{tr}F$, were not found, as we could not extend our measurements below 8 meV. But we mention that in the recent tunneling experiments of Schneider *et al.*[4] on Nb_3Sn, and of Geerk and Bangert[5] on Nb_3Al, the data could be measured down to about 3 meV, and additional structures of the α^2F function were found at surprisingly low energies.

In conclusion we have prepared tunnel junctions on V_3Si, which showed phonon-induced structures in the reduced density of states. The energetic positions of peaks and shoulders in α^2F and $G(\hbar\omega)$ agree satisfactorily. Phonons with energies near 20 meV were found to couple strongly to the electron system, in contrast to the phonons with strong contributions of the nontransition metal. For the Coulomb pseudopotential μ^* resulting from PMMR analysis, we got the very high value of 1.3, which might be taken as an indication for the presence of spin fluctuations in V_3Si. To confirm this conjecture, it is necessary to prepare better junctions on high T_c material with no proximity deformations and lower excess current. This would also help to extend the tunneling measurements to lower energies in order to prove the existence of a low-energy peak near 6 meV as expected by McKnight *et al.*[22]

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