Prospects of using nonlinear elements of the high-temperature superconductors with a A15 lattice

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It is shown that the standard coherence parameter ξ_0 for the V_3Si, Nb_3Sn and V_3Ga alloys obtained from measurements of the specific heat is too low. In this work the value of ξ_0 is determined on the basis of optical measurements. $\xi_0 \sim 300$–500 Å (instead of the generally accepted value of 50 Å) was obtained for the indicated alloys. For a length of the mean free path > 500 Å, the nonlinear, weak junctions based on these elements can be used effectively both at low T and near T_c.

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Recently, an interest has increased in nonlinear elements based on weak superconducting junctions. The potentialities that open up here are elucidated in detail in a number of review articles. The best results are obtained when weak Nb, Pb, and Sn junctions are used. A question arises whether superconducting alloys based on Nb and V with a A15 lattice structure can be used for this purpose and primarily for frequency multiplication and frequency shift. The indicated alloys have high critical transition temperature T_c to the superconducting state and high upper critical magnetic fields H_{c2}. For brevity, we will call them simply A15. Attempts to use A15 for frequency multiplication to date gave substantially worse results than using Nb, Pb, and Sn. Thus there is a consensus of opinion that the use of nonlinear A15 elements is not advisable.[1] Below we show that this is a falacy.

As is known, one of the main characteristics of weak superconducting junctions is the coherence length ξ, since the nonlinear properties depend greatly on the relation between the dimensions a of the weak junction and ξ. The strongest nonlinearity is exhibited at $a \approx \xi$. The value of ξ depends on the length of the mean free path l of electrons and on the temperature T. In all the cases, i.e., for clean and dirty superconductors and for all T, the expression for ξ contains value ξ_0, which is equal to the range of the nucleus included in the self-consistent equation for the order parameter. According to the BCS theory

$$\xi_0 = \hbar v_F / \pi \Delta_0 . \tag{1}$$

Here v_F is the velocity at the Fermi surface Δ_0 is the energy gap at $T = 0$. At $T = 0$ and $l \to \infty$ $\xi \approx \xi_0$, and at $l \ll \xi_0$ one should use $\sqrt{\xi_0 l}$ instead of ξ_0. At $T \neq 0$ in the region of applicability of the Ginzburg-Landau equations for clean and dirty superconductors we have, respectively, (see Ref. 2):

$$\xi(T) = 0.74\, \xi_0 (1 - T/T_c)^{-1/2} \text{ and } \xi(T) = 0.85 \sqrt{\xi_0 l}\, (1 - T/T_c)^{-1/2}.$$

The quantity ξ determines H_{c2}. In the limits of applicability of the G-L equations

$$H_{c2}(T) = \Phi_0 / 2\pi \xi^2 (T) . \tag{2}$$

Here $\Phi_0 = 2 \times 10^7$ G is the magnetic-flux quantum. We shall use Eq. (2) to estimate ξ in A15, for which the characteristic value of $H_{c2} \approx 2 \times 10^{15}$ Oe.[3] We obtain $\xi \approx 40$ Å. A

similar value of ξ for A15 is quoted in monographs on superconductivity (see, for example, Ref. 2). At present, it is practically impossible to fabricate nonlinear elements of such dimensions. Such small value of ξ, however, is determined by the technology used in manufacturing the A15 alloy, which produces samples with a large number of defects and impurities, rather than by the properties of the A15 material. For pure A15 materials ξ is much larger, and hence H_{c2} is much smaller.

We shall use relation (1) to estimate ξ_0. Here we should make the following comment. Usually v_F is determined from calorimetric measurements. A linear term associated with the conduction electrons is isolated in the dependence of the specific heat $C(T)$, if we assume that the contribution from the lattice to the specific heat is proportional to T^3. For A15 such method gives $v_F \approx 10^6$–10^7 cm/sec and hence $\xi_0 \approx 50$ Å. These numbers were also quoted in the review papers on superconductivity (see, for example, Ref. 2). On the basis of these numbers, A15 indeed should not be considered promising for nonlinear elements. But the calorimetric method gives values of v_F that are too low for the following reasons. First, in the alloys with a complex lattice the dependence of the lattice part of the specific heat T has a more complicated form than T^3. In the expansion in T in addition to the term $\sim T^3$ the term $\sim T$, which is associated with the lattice rather than with the electron as is commonly accepted, is also nonvanishing. As a result, the γ coefficient in the linear term of $C(T)$ is too high, i.e., v_F is too low. The discrepancy is particulary large when the phonon spectrum of the alloy has soft modes. Thus, for example, there is hardly any temperature region for Nb_3Sn in which the specific heat of the lattice can be assumed proportional to T^3.[4] Second, the specific heat of electrons contains a renormalized value, rather than v_F, which is $(1+\lambda_{ep})$-fold smaller than v_F. Here λ_{ep} is the electron-phonon interaction constant. For superconductors with a high value of $T_c\lambda_{ep}$ is close to unity, and the true value of v_F differs from the renormalized value almost by a factor of 2. This fact is usually also disregarded. The value of v_F deprived of the indicated errors is given by the optical method. The algorithm for determining by the optical method the value of v_F, which is averaged over the real Fermi surface, is given in Ref. 5.

Table I gives the data pertaining to certain A15 alloys for which the optical measurements were performed., The value of v_F obtained by using the optical method are listed in column 2 and the values of Δ_0 obtained from the tunnel measurements are listed in column 4. In the presence of anisotropy of the gap the largest value of Δ_0 is quated. For V_3Ga the value of Δ_0 was determined from $T_c = 16$ K and from Δ_0/kT_c is 1.76. The values of ξ_0 are listed in column 6.

TABLE I

Material	v_F, 10^8 cm·sec^{-1}	References	Δ_0, meV	References	ξ_0, Å
Nb_3Sn	0.48	6	2.35	[8]	430
V_3Si	0.36	7	2.8	[9]	270
V_3Ga	0.65	6	2.43	–	560

It can be seen in Table I that ξ_0 in A15 is much larger than ξ obtained in real samples, which indicates that l is very small in the latter. It also follows from Table I that in A15 $\xi_0 \approx 300$–500 Å, which is much larger than the generally accepted value of 50Å;[2] this changes the view on A15. Working weak junctions can be effectively produced from A15. First, we must have A15 alloy with sufficiently large value of l (larger than 500 Å). But it is not advisable to strive for values of $l \gg \xi_0$, since ξ in this case remains almost constant, and the difficulties of producing the alloy increase; moreover, a certain amount of impurities is useful.

Thus, if the high-temperature alloys based on Nb and V with a A15 lattice structure have an acceptable quality, the weak junctions based on these alloys can work efficiently both at low T and near T_c. To reduce the noise, it is advisable to work at low T. But high T_c increases the reliability of the weak junctions, and hence reduces the harmful role of possible random overheating.

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