Radiation damaged MgB$_2$: a comparison with A15 superconductors

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Abstract. In the present paper we discuss in detail experiments of radiation damage and their effects on MgB$_2$ properties (T$_c$, resistivity, critical field, gap), making constant reference to similar experiments performed in the seventies and eighties on A15 superconductors (Nb$_3$Sn, V$_3$Si). We will show that the overall behaviour of MgB$_2$ and A15s is surprisingly similar, pointing out that similar mechanisms (smearing of density of states) plays a role at high radiation doses, whereas, at low radiation, two-band effects mainly determine the MgB$_2$ behaviour.

1.Introduction

Since the discovery of superconductivity in MgB$_2$ many aspects of its complex phenomenology have been clarified. In particular, the main feature of this compound is the presence of two gap ($\sigma$ and $\pi$) superconductivity. Multiple gap superconductivity has been considered from the theoretical point of view since the fifties and it was already clear that for multigap superconductivity to be observed, it was necessary to have a negligible interband impurity scattering. In pure MgB$_2$ interband scattering is intrinsically low, the two bands have comparable density of states (DOS) and the gaps are quite different from each other, so that can be unambiguously evidenced.

To get a deeper insight in the mechanisms of superconductivity in MgB$_2$, also in view of fully exploiting its potentialities towards applications, it is very important to precisely determine the effect of disorder on superconductivity, and to understand the relative role of interband and intraband scattering.

Radiation damage is an advantageous technique in this respect, because it allows to introduce controlled disorder without doping effects. Several experiments of irradiation carried out with neutrons and alpha particles, strongly modifying the normal and superconducting properties of MgB$_2$, have been recently reviewed in Ref. 1. At high disorder level the merging of the gaps predicted by the two band model has been observed but it occurs at a critical temperature much lower than predicted for isotropic MgB$_2$. This proves that the interband scattering is able to drive from two to single gap superconductivity, but suggests that in strongly irradiated samples also other effects cooperate to the suppression of superconductivity.

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2. Tc suppression with disorder in MgB2

The first experiments of Tc as a function of disorder in MgB2 showed a lack of correlation. Often samples with optimal Tc values exhibited resistivity values that were even one or two orders of magnitude higher than the few μΩ cm found in a relatively small number of single crystals and films. Given the two-gap model of superconductivity, this fact was first considered as a possible evidence of the band disparity of the electronic states [2], but J. Rowell suggested that the resistivity increase in most cases could be simply ascribed to a week connection between the grains which causes a reduction in the effective current-carrying cross-sectional area of the sample [3]. The reduction of critical currents in high resistivity samples supported nicely this simple model, therefore the “Rowell model” has been quite systematically adopted to correct resistivity data to account for sample granularity. This is done in this paper as well.

After first pioneering experiments, it was soon realized that the better way to effectively and uniformly damage MgB2 samples was to use α particle or neutron irradiation. It can be observed that plotting Tc (normalized to the undamaged value Tc0) as a function of dose produced an overall behaviour analogous to what observed in the past for the “classical” A15 superconductors. In Fig.1 (a) and (b) Tc/Tc0 are plotted as a function of α particle and neutron fluence for MgB2 compounds and selected A15 samples. All the data follow a very similar behaviour: this is quite surprising given the deep material structure difference.

To shed more light on the relationship between the suppression of superconductivity and the defects introduced by irradiation, the critical temperature can be plotted as a function of resistivity, which gives a “global” measure of the introduced disorder level. Fig.2 (a) shows Tc as a function of the residual resistivity ρ0 for irradiated MgB2 films [5] (all the Tc vs ρ0 data follow the same universal behaviour when resistivity data are corrected using the “Rowell model” [1]). Tc values decrease linearly and the intercept on the resistivity axis, that can be regarded as the maximum resistivity attainable before superconductivity is destroyed, is around 85 μΩ cm.

The two-gap theory of superconductivity, that applies to MgB2, in the strong interband scattering limit predicts a saturation of the critical temperature, which has been estimated to be around 20K [8]. The lack of any saturation in Tc vs ρ0 near 20 K, suggests that factors other than interband scattering might play a role in suppressing superconductivity. On the other hand the linear scaling of Tc with ρ0
indicates that a strong correlation exists between the mechanisms increasing resistivity (scattering with atomic scale defects) and the ones reducing $T_c$. As presented in Fig. 2 (a) A15 superconductors exhibit a similar behaviour (data for Nb$_3$Sn and V$_3$Si are from Ref. 9). Looking at this plot, MgB$_2$ would seem to be seriously affected by disorder: for a resistivity value of about 70 $\mu$Ω cm $T_c$ is reduced down to 20% of $T_{c0}$, while for A15s at the same resistivity value the $T_c$ is around 60-80% of $T_{c0}$. However, this plot does not take into account the band structure details which change from material to material. The appropriate quantity that measures the amount of disorder is the scattering rate, $\Gamma=\rho_o\Omega_p^2/4\pi$, where $\Omega_p$ is the plasma frequency. $T_c/T_{c0}$ is reported as a function of $\Gamma$ in Fig. 2 (b). Due to the remarkable contribution of the plasma frequency (that, as known from the literature, for MgB$_2$ is nearly twice that of A15s) this plot emphasizes that at high levels of disorder MgB$_2$ is indeed much less affected by defects in respect to A15 compounds.

![Figure 2. $T_c/T_{c0}$ as a function of residual resistivity $\rho_0$ (a) and as a function of the scattering rate $\Gamma$ (b) for MgB$_2$ [5], Nb$_3$Sn and V$_3$Si [9].](image)

To conclude, it is worth emphasizing that the defects produced by irradiation in A15 compounds were both antisite defects and atom displacements from their lattice sites [4,10,11]. In the case of MgB$_2$, from an analysis of the activation energies, it is possible to exclude the presence of antisite defects though there are no clear indications on whether Mg or B displacements mainly occur [1].

3. Upper critical field

The upper critical field of type II superconductors is strongly sensitive to defects, which reduce the electron mean free path and, consequently, the coherence length, producing an increase in $H_{c2}$, important for applications. This fact has been one of the driving force to study radiation damage in superconductors. Many studies are reported in the recent literature on MgB$_2$. In particular in Ref. 12, a large collection of MgB$_2$ thin film data is presented and analysed, whereas systematic studies of thin films under a-particles and neutron irradiation is presented in ref. 13 and 14. In Fig. 3 (a) the $H_{c2}$ values extrapolated at zero temperature of MgB$_2$ and A15 compounds is reported as a function of the reduced critical temperature. This plot suggests that despite differences related with multi-band nature and mechanisms which suppress superconductivity, $H_{c2}(0)$ follows a universal behaviour: with increasing disorder $H_{c2}(0)$ raises because the reduction of mean free path carries the superconductor in dirty limit, then the suppression of condensation energy prevails and $T_c$ and consequently $H_{c2}$ values go down.

In Fig. 3(b) the slope of $H_{c2}$ close $T_c$, $H'_{c2}$, versus $T_c/T_{c0}$ is plotted for MgB$_2$ [13, 14], V$_3$Si [15] and Nb$_3$Sn [16]. The overall behavior is again similar, but in MgB$_2$ $H'_{c2}$ is nearly ten times lower. From
these data the quantity \( N(0)(1+\lambda) \) (\( N(0) \) is the DOS at the Fermi energy and \( \lambda \) is the electron-phonon interaction parameter) vs \( T_c/T_{c0} \) can be calculated and is reported in Fig. 3 (c) (see Ref. 1). It is clear how the renormalized DOS comes out to be much lower in MgB\(_2\) than in A15s, consistently with the theoretical \( N(0) \) values reported in the literature.

The suppression of \( N(0)(1+\lambda) \) with disorder is quite strong in V\(_3\)Si and Nb\(_3\)Sn and much weaker in MgB\(_2\). In any case the renormalized DOS in MgB\(_2\) significantly decreases (by a factor 2) at high disorder levels.

4. Gap values

Many experiments have investigated the evolution of the energy gaps of MgB\(_2\) with disorder. Among these of special relevance are the specific heat measurements reported in Ref.s 17 and 18 on neutron irradiated samples, as well as those from point contact and tunneling measurements [19, 20]. The importance of these experiments was to provide a definitive evidence of the merging of the two gaps to a single one as an effect of interband scattering. However, the merging takes place at lower temperature in respect to the saturation temperature predicted for isotropic MgB\(_2\) again indicating that besides interband scattering, other mechanisms could play a role in suppressing superconductivity in disordered MgB\(_2\).

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**Figure 3** (a) \( H_{c2}(0) \), (b) \( H'_{c2} \), and (c) \( N(0)(1+\lambda) \) versus \( T_c/T_{c0} \) for MgB\(_2\) [13, 14] (values measured with the magnetic field applied parallel to the ab plane in a thin film), V\(_3\)Si [15] and Nb\(_3\)Sn[16].

The data are compared with available data for MgB\(_2\) [17,18,19] (full symbols).

**Figure 4**: \( 2\Delta(0)/k_BT_c \) vs. \( T_c/T_{c0} \) for disordered A15 films [21, 22] and Nb [23] (empty symbols). The data are compared with available data for MgB\(_2\) [17,18,19] (full symbols).
The comparison with disordered A15s emphasizes an important feature. Plotting the reduced gap $2\Delta(0)/k_BT_c$ for disordered A15 samples with $2\Delta\sigma(0)/k_BT_c$ for irradiated MgB$_2$ as a function of $T_c/T_{c0}$ (see Fig. 4) leads to an universal behaviour. The reduced gap which in clean samples assumes values equal or larger than the BCS value, with increasing disorder drops systematically below this value suggesting that a break-down of the BCS approach for highly disordered samples could take place.

5. Discussion
The interband scattering as predicted by the two band theory nicely explains the reduction of $T_c$ in MgB$_2$ at low level of disorder, whereas at high level of disorder it is responsible of the merging of the gaps. However, to have a complete understanding of the degradation processes of the superconducting properties, and in particular of the $T_c$ vs $\rho_0$ curve, it appears to be necessary to consider the ideas proposed to explain the suppression of $T_c$ in damaged A15s. The model proposed by Testardi and Mattheis for A15 [24], assumes a broadening of the DOS produced by the electron scattering on defects, and accounted very well for the reduction of the DOS and the consequent suppression of superconducting properties. The application of this model to MgB$_2$ [25] proves that the DOS is affected by intraband scattering only at high level of disorder. This is shown in Fig. 5 where $N(\Gamma)/N(0)$ is plotted as a function of relaxation rate $\Gamma$ for the $\sigma$- and $\pi$-band of MgB$_2$ [25] and for V$_3$Si and Nb$_3$Sn [23]. In the case of A15s, on the contrary, the DOS drops even at low level of disorder.

![Graph of $N(\Gamma)/N(0)$ vs $\Gamma$ for MgB$_2$, V$_3$Si, and Nb$_3$Sn](image)

**Figure 5.** $N(\Gamma)/N(0)$ as a function of relaxation rate $\Gamma$ for the $\sigma$- and $\pi$-band of MgB$_2$ [25], V$_3$Si and Nb$_3$Sn [23].

This is confirmed experimentally both by critical field slope measurements (Fig. 3c) as well as by measurements of the Sommerfeld constant by specific heat [17, 18]. By carefully taking into account both the two band effects and the effect of DOS reduction, an overall satisfactory agreement between theory and experiment can be obtained, including the $T_c$ vs $\rho_0$ dependence, as proved in Ref. 25.

In summary, we have shown that the comparison with A15 has shed light on the mechanisms involved in the $T_c$ degradation in MgB$_2$.

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