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The effect of magnetic and non-magnetic ion damage on the surface state in SmB_6

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ABSTRACT

SmB_6 is a Kondo insulator with a band structure that is topologically distinct from the vacuum. This is theoretically predicted to produce metallic topological surface states that are robust to perturbations that do not break time reversal symmetry, such as non-magnetic defects. However, the surface state may be destroyed by an impurity with a sufficiently large magnetic moment. In order to test this prediction we show measurements of the resistance of the surface state of single crystals of SmB_6 with varying levels of damage induced by magnetic and non-magnetic ion irradiation. We find that at a sufficiently high concentration of damage the surface state reconstructs below an amorphous damaged layer, whether the damage was caused by a magnetic or non-magnetic ion.

1. Introduction

SmB_6 is a known Kondo insulator in which hybridization of the *f* and conduction electrons opens a small energy gap at the Fermi energy [11]. This produces a diverging resistivity as temperature decreases, as expected, but the resistivity saturates at around 3 K. The band structure of SmB_6 was recently predicted to be topologically non-trivial [6]. At the interface between a topologically non-trivial insulator and the trivial vacuum the energy gap is predicted to close, giving rise to metallic surfaces states on the crystal [4,7,15]. The low temperature resistivity saturation in SmB_6 was recently shown to be because of metallic states on the surface [17,20,12], but the topological nature of those states is still a matter of intense debate.

One of the predicted properties of a topologically protected surface state is that it is robust to the back-scattering of electrons by perturbations that do not break time reversal symmetry, such as non-magnetic impurities and defects. However, magnetic impurities are predicted to cause a large reduction in the conductivity of the surface state. Indeed, recent work showed that bulk doping of SmB_6 with magnetic Gd ions destroyed the surface state, while doping with non-magnetic Y ions did not [13]. However, this kind of bulk doping inevitably disrupts the bulk band structure of the material, as well as the surface. A method of perturbing the surface of the crystal while not affecting the bulk is therefore desirable. In previous work on SmB_6 the surface was damaged while the bulk was left pristine using irradiation with Xe and Ar ions. The robustness of the surface state to this non-magnetic perturbation was tested by measuring the resistance of the sample after damage to progressively deeper into the crystal [18]. The crystals were damaged to a final depth of greater than 200 nm and therefore significantly deeper than current estimates of the intrinsic surface state which is of order 10 nm [16,3,2,14,9]. In that work the data were consistent with a model in which the surface state was reconstructed below a poorly conducting damaged layer. This is consistent with the theoretical predictions for a topological insulator [21,16].

Here, we report on further work to measure the resistance of SmB_6 single crystals damaged through ion irradiation. In contrast to simple expectations irradiation with magnetic Fe ions does not destroy the surface state, and we present evidence that the surface state is still reconstructed below the damaged layer. In addition, through low concentration damage of the surface state with non-magnetic ions, we show that the low temperature resistance of the sample initially increases and then at higher concentrations decreases as before.

2. Method

Single crystals of SmB_6 with approximate dimensions of 400 μm × 150 μm were grown using Al flux and polished down to around 100 μm thick. In order to measure the resistance *R* of the

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Table 1
Parameters used in the ion-irradiation of SmB_6. The damage is quantified in units of displacements per atom (DPA).

Depth (nm)	Damage (DPA)	Ion	Energy (keV)	Ion fluence (cm^{-2})	Time (s)
17.5	1	Fe^+	20	7×10^{14}	45
105	1	Fe^+	160	7×10^{14}	62
160	0.001	Ar^+	200	1.1×10^{12}	10
160	0.01	Ar^+	200	1.1×10^{13}	112
160	0.1	Ar^+	200	1.1×10^{14}	1129
160	1	Ar^+	200	1.1×10^{15}	7200

samples, four Pt wires were spot welded to the top face of the crystal. A four point resistance measurement was then performed using an AC resistance bridge. The surface damage of the samples with magnetic ions was produced using Fe^+, and non-magnetic damage with Ar^+ ions. The depth and level of damage was calculated using the SRIM Monte Carlo code in the full cascade mode [22]. The ion, acceleration energy, fluence and exposure time for each ion exposure are shown in Table 1. The stated depth of damage was defined as the depth at which the damage level is half of the maximum damage, as discussed previously [18]. The resistance of each sample was measured as a function of temperature down to 1.8 K, after the crystals were damaged on the top surface, and then again after damage to the bottom surface. This was repeated for each round of damage, with the leads permanently attached for the duration of the experiment. Three samples were damaged with magnetic ions and another sample was damaged with non-magnetic ions.

3. Results

Fig. 1 shows the sheet resistance, $R_s = R2w/l$, where w is the width of the sample and l is the distance between voltage contacts, as a function of temperature T for one of the samples damaged by irradiation with Fe^+ ions to progressively greater depths into the surface, as described above. Note that after the ion damage the low temperature saturation in the resistance is still present in the damaged sample, but the magnitude is monotonically reduced. Significant damage to SmB_6 is known to destroy the Kondo gap, making the damaged region a poor conductor [10]. This means that one effect of damaging the surface of SmB_6 is to produce a new conducting channel in the sample. The important question though is the fate of the intrinsic surface state after the damage. To investigate this it is useful to take the inverse of the residual sheet resistance at low temperatures to give the residual sheet conductance G_{S0}. For all three samples this is plotted in Fig. 2 as a function of d, the sum of the depth of damage to the top and bottom surfaces. Data from previous work on the effect of non-magnetic ion damage with Xe and Ar ions are also shown in Fig. 2 for comparison.

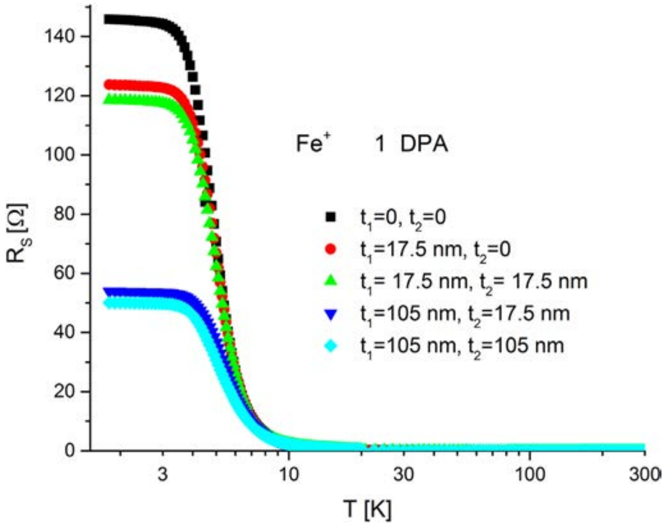

Fig. 1. Temperature dependence of the sheet resistance R_s of one of the SmB_6 crystals after differing depths of Fe^+ ion-irradiation damage to each face. t_1 is the depth of damage to the top face of the sample (to which contacts were made), t_2 is the depth of damage to the bottom face.

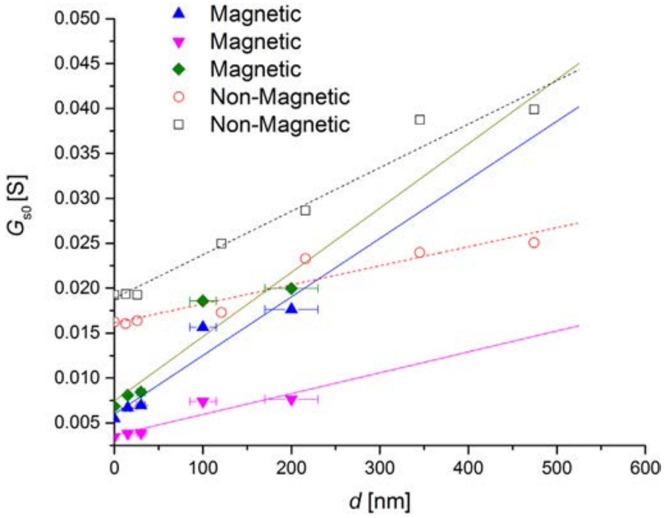

Fig. 2. Residual sheet conductance G_{S0} of SmB_6 as a function of the effective depth of ion-radiation damage d, given by the sum of the damage depth to the top and bottom faces. Closed symbols are data for damage with magnetic Fe^+ ions on 3 different samples, and open symbols are previously published data of damage with non-magnetic Ar and Xe ions on 2 different samples [18]. Lines are fits to the formula $G_{S0} = 1/R_{SS} + d/2\rho_{DL}$, where ρ_{DL} is the resistivity of the damaged layer.

A scenario in which the surface state is not destroyed, but reconstructs below the damaged layer, can be modeled using the equation $G_{S0} = 1/R_{SS} + d/2\rho_{DL}$. This describes a parallel resistor model in which the first term represents the intrinsic surface state with sheet resistance R_{SS}, given by the sheet resistance of the undamaged sample at low temperature. This term is assumed to be independent of d. The second term represents the poorly conducting damaged region and is proportional to the damage depth. This equation has been fitted to the experimental data in Fig. 2, where ρ_{DL} is the resistivity of the damaged layer and is a fitted parameter calculated to be in the range 0.7–2.2 mΩ cm, which is in reasonable agreement with previous ion and neutron damage studies [18,10]. While there are deviations in the data from the fitted model, importantly the data are more consistent with this equation than a fit that is linear in d with a zero intercept. A zero intercept would be the expected behavior had the surface state been destroyed by the damage. Therefore, we conclude that the surface state has not been destroyed by the magnetic ion damage, but instead the state reconstructs below the damaged layer, as seen in our work on non-magnetic damage. Studies to greater depths may be useful, though the data shown support our interpretation. Deviations of the experimental data from our fitted model may arise from inhomogeneity in the damage across the surface, or the effects of a damage profile as a function of the depth that is more complicated than the simple step function assumed here. Work to further investigate these inhomogeneities is ongoing. The variation in the sheet resistance between samples is consistent with values reported in the literature. This may be the result of intrinsic variations in sample quality or a sensitivity of the sample surface to mechanical treatment. These two factors are

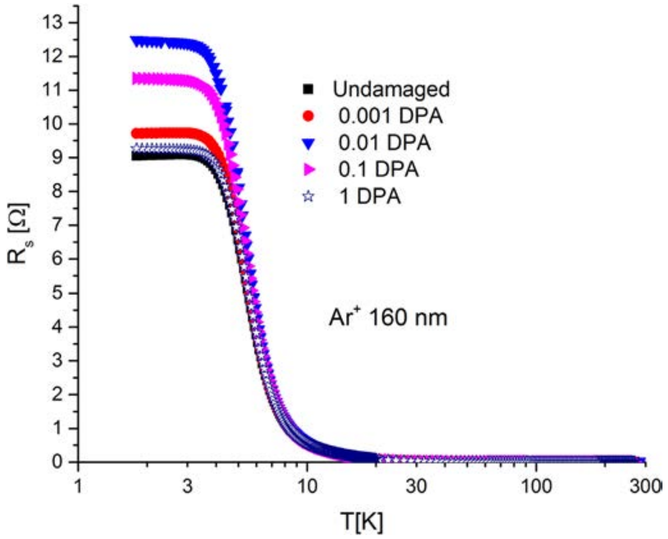

Fig. 3. Temperature dependence of the sheet resistance R_s of an SmB_6 crystal after differing concentrations of Ar^+ ion-irradiation damage to a depth of 160 nm.

likely to also account for the variation in the fitted resistivity of the damaged region.

The insensitivity of the surface state in SmB_6 to the magnetic damage produced by the Fe ion irradiation is perhaps surprising given the expectation that a topological surface state would be destroyed by time reversal symmetry breaking perturbations. However, this result is consistent with measurements of the resistivity under an applied magnetic field. It has been shown that the application of large magnetic fields up to 60 T is insufficient to close the Kondo gap, or destroy the low temperature saturation of resistance [5]. This implies that the direction of the spin of the surface state electrons may be insensitive to magnetic field and therefore to magnetic impurities. Therefore, the results presented here are still consistent with a topological surface state in SmB_6. It must also be considered that perhaps the surface state reconstructs to a region in the sample that is free of magnetic impurities. This scenario will have to be investigated in future work.

Our work implies that the physical interface between the SmB_6 and the vacuum may not be the location of the conductive surface state, depending on the treatment of the surface. This may be relevant to surface sensitive measurements such as the photoemission or scanning tunneling spectroscopy. In addition the location of the conducting state may be important in constructing heterostructures of SmB_6 with magnetic or superconducting layers as has been proposed to search for exotic states such as Majorana fermions, for example [8,1,19].

In the work discussed so far the damage caused has been sufficiently concentrated to destroy the Kondo gap in the damaged layer and lead to a reconstruction of the surface state. It is now interesting to consider the effect of damage levels at lower concentrations, and whether there is any increase in scattering as a result of the damage. So finally, Fig. 3 shows the sheet resistance as a function of temperature of an SmB_6 crystal damaged with Ar^+ ions to 160 nm with a progressively greater concentration of damage. Note again that the low temperature resistance saturation is not destroyed but now the magnitude is no longer a monotonic function of the damage. At low levels of damage the sheet resistance is modestly increased by the damage, likely because of an increase in small angle scattering of the surface state electrons. Once the damage becomes sufficiently concentrated the resistance begins to fall because of the effect of the addition of the conduction channel from the heavily damaged layer, as discussed above. These data suggest that a low concentration of non-magnetic disorder may have a small effect on the conductivity of the intrinsic surface state, but once the damage is sufficiently large the surface state reconstructs below the damage.

4. Conclusion

In conclusion we have shown that heavy irradiation of the surface of SmB_6 crystals with Fe^+ ions does not cause the destruction of the intrinsic surface state, but instead, as in the case of non-magnetic ion damage, the surface state reconstructs below the poorly conducting damaged layer. While this implies some robustness of the surface state to magnetic damage, this is qualitatively consistent with measurements under an applied magnetic field. This is not inconsistent with the surface state being topological in nature, it merely implies that the spin direction of the surface electrons is relatively insensitive to magnetic field. Light damage by non-magnetic ions was shown to cause an increase in the sheet resistance of the crystal, likely because of increased scattering, but at heavier irradiation doses the resistance was seen to decrease as before. This implies some sensitivity of the surface state to disorder which will require further investigation. These results have important implications for future studies of SmB_6, and may also be relevant to technological uses of SmB_6 in heterostructures with magnetic layers, for example.

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