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Review

MgB_2 tunnel junctions and SQUIDs

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Abstract

Recent advances in the realization and understanding of MgB_2 tunnel junctions and SQUIDs are surveyed. High quality MgB_2 junctions with suitable tunnel barriers have been realized based on both oriented and epitaxial thin MgB_2 films. Multiband transport properties, such as the existence of two energy gaps, phonon spectra and anisotropy have been investigated with these junctions. We review the suitability of different barrier materials and recent advances in obtaining reproducible all-MgB_2 Josephson junctions for superconducting electronic circuitry. The development of epitaxial thin films has also led to high-quality multiband MgB_2 SQUIDs and magnetometers that operate at high temperatures. The multiband nature of MgB_2 provides new phenomena such as the Leggett mode. Manipulating the different phases of the condensates could lead to novel MgB_2 devices with phase degrees of freedom.

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Contents

1. Introduction . . . 188
2. Epitaxial thin films . . . 189
3. Quasiparticle and Josephson tunnel junctions . . . 190
   3.1. Multiband transport . . . 190
   3.2. MgB_2–insulator–metal junctions . . . 191
   3.3. Suitable barrier materials for all-MgB_2 Josephson junctions . . . 191
4. SQUIDs and magnetometers . . . 192
5. Novel multiband phase devices . . . 193
6. Conclusion . . . 194
   Acknowledgements . . . 194
   References . . . 194

1. Introduction

After the discovery of superconductivity in MgB_2 [1], very fast initial progress was made in the realization of thin films, junctions and SQUIDs. Within a couple of months, multilayer MgB_2 Josephson junctions [2] and

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MgB_2 SQUIDs [3] had been realized. This large initial research effort was motivated by the opportunities that MgB_2 gives to applications.

First of all, compared to high-T_c materials, MgB_2 is much more metallic, with very much lower resistivity, which results in a lower anisotropy. The low resistivity is especially beneficial to the noise properties in SQUIDs. Additionally, the c-axis coherence length in MgB_2 is about 5 nm, which is larger than in high-T_c superconductors (HTS). An advantage of longer coherence length materials in junctions is that the effect of a degraded layer with lower T_c near the electrode-barrier interface is reduced. The coherence length in the MgB_2 a–b plane is even larger, suggesting that a–b plane junctions are even more advantageous for applications.

Secondly, the critical temperature of 40 K of MgB_2 is attractive from a cooling point of view [4]. Superconducting rapid single flux quantum logic (RSFQ) circuitry is now typically based on low-T_c Nb/Al_2O_3/Nb technology, which has to be cooled to 4–5 K. HTS oxide technology, on the other hand, allows for a higher operating temperature. However, due to bit-error rates at elevated temperatures, 20–30 K is generally regarded as the optimal operating temperature. In that sense, all-MgB_2 junctions are at least as attractive, avoiding the materials science issues that are still hampering HTS technology, and allowing the use of compact cryocoolers. For a heat load of 1 W the advantages of cooling to 25 K instead of 4.5 K are, for example, a volume reduction from 0.2 to 0.01 m^3 and an input power reduction from 1500 to 150 W [5].

A spread in junction properties, particularly I_c, of less than 2% is required in order to fabricate RSFQ circuitry with large numbers of junctions. This small spread has been achieved in Nb/Al_2O_3/Nb technology, but has not yet been possible with HTS and is still a major challenge for MgB_2 junction technology.

Finally, the product of the critical current and the normal state resistance, I_cR_N for unshunted junctions, is predicted to be high compared to that of low-T_c materials [6], especially in the case of tunneling in the crystallographic MgB_2 ab-plane. The large energy gap of MgB_2 should also allow higher frequency operation of SIS detectors.

Parallel to the initial development of junctions and SQUIDs, the notion started to develop that MgB_2 is a model example of a multiband superconductor [7], with a comparable weight of the respective bands. This notion spurred a second urge for MgB_2 junctions, this time as devices for spectroscopic measurements of the electronic properties of MgB_2. The conductance through a superconductor–insulator–normal metal tunnel junction is proportional to the density of states in the superconductor, and an MgB_2–insulator–metal junction is, therefore, an ideal spectroscopic device, where the metal can either be a normal metal or a superconductor with a lower-critical temperature. Needless to say, that in order to probe the anisotropic transport properties of MgB_2, it is essential that the MgB_2 electrode is oriented. Oriented, or even in-plane epitaxial, devices also provide reproducibility advantages for all-MgB_2 Josephson junctions for RSFQ and SQUIDs for magnetic field sensing applications.

Here, we will review the state of the art of MgB_2 devices and describe recent advances in the realization of thin films, tunnel junctions (both for spectroscopic purposes as well as superconducting electronics) and SQUIDs. Finally, novel MgB_2 devices will be discussed, that are uniquely based on the multiband character of MgB_2.

2. Epitaxial thin films

The main requirements on thin films for most devices are a high and stable transition temperature (no degradation upon exposure to the environment and structuring), a smooth and dense morphology, and an oriented or even epitaxial crystal structure. The influence of the film density and grain connectivity on the transport properties was discussed by Rowell [8].

Films with very high and stable transition temperatures (39 K) have been obtained by means of ex-situ deposition techniques [9], in which a B film is typically exposed to a high-pressure Mg vapor at high temperatures, to let it react to MgB_2. However, the large surface roughness and low density of such films make these films unsuitable for most device applications.

In-situ MgB_2 film growth techniques (see Refs. [10–15] for early thin film results) deal with three major challenges. The first challenge lies in avoiding the oxidation of Mg and B, which generally requires very pure target materials and high-vacuum deposition conditions. The second complication is the large difference in vapor pressures of B and Mg, the Mg vapor pressure being orders of magnitude higher than that of B. Thirdly, the Mg sticking coefficient is very low above about 300 °C. Most growth methods are, therefore, limited to low temperatures, since not sufficient Mg can be provided at elevated temperatures, typically leading to films with a reduced T_c, enhanced resistivity as compared to bulk MgB_2 and a low degree of orientation.

Beneficially, the growth of MgB_2 is found to be kinetically and absorption limited [16], meaning that the Mg does not escape from the film after the right phase has formed during growth, and that the right phase will form as long as sufficient Mg vapor is present. A number of growth techniques explicitly benefit from these properties by independently tuning the B and Mg fluxes, or by simply providing a large excess of Mg flux. The independent flux tuning is used for example in combinations of pulsed-laser deposition of Mg with sputter-deposition of B [17], or e-beam evaporation of B with evaporation of Mg [13], or sputter-deposition of B with evaporation of Mg [18]. When the Mg vapor can be confined close to the film, as with a closed container, high quality eptiaxial films have recently been obtained [19,20].

The best epitaxial MgB_2 films in terms of high-T_c, low resistivity, smoothness, and degree of orientation have