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Far-Infrared Carrier Dynamics in Superconducting MgB₂

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Abstract. We have performed optical-pump terahertz-probe measurements in transmission on MgB₂ thin films in the superconducting state. The initial optical perturbation of the superconducting condensate and subsequent pair recovery display a strong fluence dependence.

1. Introduction

The announcement in January 2001 of the discovery of bulk superconductivity in MgB₂ at T_c ~ 39 K [1] has generated a great deal of excitement since T_c is higher by nearly a factor of two in comparison to other previously known simple intermetallic superconductors (e.g., Nb₃Ge, T_c ~ 23 K). Far-infrared spectroscopy is a useful technique to characterize the low energy states in superconductors. Recently, the superconducting gap in MgB₂ has been studied using terahertz time-domain spectroscopy [2].

All-optical ultrafast time-resolved spectroscopy has also proven to be sensitive to the low energy states of correlated electron materials [3]. Combining ultrafast optical and far-infrared techniques to directly probe the low energy conductivity dynamics with picosecond resolution has allowed us to simultaneously measure the dynamics of quasiparticles and superconducting pairs in high-T_c superconductors [4], showing a similar temperature dependence of the relaxation time as in [3]. Time-resolved far-infrared studies of superconducting pair breaking have been performed on lead which is a conventional superconductor with T_c = 7 K [5]. However, given the low value of T_c in Pb, it is difficult to perform temperature and fluence dependent studies in the superconducting state. MgB₂, having a considerably higher T_c, offers the exciting possibility to look at the time-resolved far-infrared dynamics of a BCS-like superconductor in considerable detail. In the following we present our time-resolved studies of the pair breaking and recovery in MgB₂.

2. Experimental Methods

The MgB₂ films used in these studies had thicknesses of approximately 50 nm and 100 nm with T_c ~ 34 K [8]. The experiments were performed using 1-mJ 150-fs 1.5-eV pulses at 1 kHz from a commercial regeneratively amplified system. The
1.5 eV pulses were used to photoexcite the sample and generate and detect the terahertz (THz) pulses in ZnTe. Further details of the film growth and experiment are described elsewhere [4,6].

3. Results and Discussion

Figure 1(a) shows the THz pulses transmitted through the MgB$_2$ film at 35 K (above T$_c$) and at 7 K. The phase shift is the so-called kinetic inductance due to superconductor pairing (i.e. the conductivity due to the superconducting pairs is purely imaginary with a 1/ω dependence that results in the observed phase shift in the time domain). The increase in amplitude below T$_c$ is due to the increase in transmission above the superconducting gap compared to the normal state transmission. This is evident in Fig. 1(b) which shows the amplitude of the Fourier transform in the superconducting state divided by the amplitude in the normal state (35K). Below 30 K a gap opens up and increases in magnitude with decreasing temperature. The inset shows the gap Δ as a function of temperature as determined from data analysis using Mattis-Bardeen formulae [7] — the dashed line is a fit showing the BCS-like behavior of MgB$_2$. Fig. 1(c) and (d) show the temporal evolution of the complex conductivity at 7 K following photoexcitation with a fluence of ~1μJ/cm$^2$. Clearly, $\sigma_{IM}$ (Fig. 1(c)), shows a decrease corresponding to Cooper pair-breaking. Correspondingly, there is an increase in the real conductivity $\sigma_{RE}$ (Fig. 1(d)) due to an increase in the number of quasi-particles. Fig. 1(d) shows that the filling in of the superconducting gap takes several ps. At 300 ps (curves with open diamonds) the superconducting state has partially recovered. This is shown more clearly in Fig. 2(a) where $\sigma_{IM}$ and $\sigma_{RE}$ (1

![Figure 1](image-url)

**Fig1.** (a) Transmitted E-field above (dashed line) and below (solid line) T$_c$. (b) Normalized transmission vs. frequency at various temperatures showing the gap opening — the inset show the gap versus temperature. Temporal evolution of (c) $\sigma_{IM}$ and (d) $\sigma_{RE}$ following photoexcitation.
THz) are plotted as a function of time. The superconducting pair recovery time as a function of temperature is shown in 2(b). The dynamics are much slower than in high-\(T_c\) materials which is consistent with the observation that the lifetime goes as \(1/\Delta\) [3]. In addition, the temperature dependence is consistent with the gap model where the lifetime increases upon approaching \(T_c\) due to the anharmonic decay of \(2\Delta\) phonons (phonon bottleneck) [3], while at lower temperatures the lifetime increases due to a low density of quasiparticles (bi-particle recombination bottleneck) [8]. Fig. 2(c) shows the fluence dependence of the risetime that corresponds to superconducting pair breaking (see Fig. 1(c) and (d)). The solid lines are fits with a two-exponential rise followed by a single exponential decay. The rise consists of a fast resolution limited component (~1 ps) and a slower (~15 ps) component. This slow risetime at lower fluences could result from phonon-mediated pair breaking following the initial fast quasiparticle avalanche pair-breaking process. This is consistent with the fact that at higher initial quasiparticle densities (e.g., 20 \(\mu\)J/cm\(^2\)) the risetime is dominated by the fast resolution limited response. In conclusion, we have performed the first time-resolved far-infrared studies on the new superconductor MgB\(_2\).

References