Fabrication and femtosecond photoresponse studies of MgB₂ superconducting thin films

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ABSTRACT

We present fabrication and optical time-resolved photoresponse characterization of MgB₂ superconducting thin films. The films were prepared on crystalline and flexible plastic substrates by vacuum co-deposition of B and Mg precursors and high-temperature annealing in an Ar or vacuum atmosphere. The post-annealed films exhibited very smooth surfaces and amorphous structures with nanocrystal inclusions. The best films exhibited the critical temperature \( T_c \) of up to 38 K, the transition width of 1 K, and the current density \( j_c \) at 4.2 K of about 10⁶ A/cm². In our pump-probe photoresponse experiments, we used 100-fs-wide optical pulses generated by a Ti:Sapphire laser. The pump and the probe beams had 800-nm wavelength and the measurements were performed in the temperature range from 3.5 K to room temperature. The transient reflectivity change (\( \Delta R/R \)) signals exhibited around 300-fs (10%–90%) risetime. At room temperature and far above \( T_c \), \( \Delta R/R \) was characterized by a ~160-fs, single-exponential decay, interpreted as the electron-Debye-phonon interaction time. Below 60 K and in the superconducting state, the \( \Delta R/R \) photoresponse was biexponential, with the initial femtosecond decay followed by a much slower, several-ps-long relaxation. We associate the latter slow relaxation with the electron-phonon interaction related to the Cooper pair recombination dynamics. The existence of this signal above the nominal \( T_c \) of our films, we tentatively interpret as the presence of superconducting fluctuations in our MgB₂ films. Our work gives the first insight into the carrier dynamics in MgB₂ by time-resolved experimental studies of the Cooper pair breaking and thermalization mechanisms for the films perturbed by femtosecond optical excitations.

Keywords: pump-probe, ultrafast photoresponse, MgB₂ thin films, superconductor thermalization, Cooper-pair recombination.

1. INTRODUCTION

The recent discovery of superconductivity at 39 K in magnesium diborides has stimulated very intensive investigations of the basic physical properties, as well as triggered studies devoted to both high-power and electronic applications of this new superconductor. Magnesium diborides exhibit a simple crystalline structure, with graphite-like B sheets separated by hexagonal layers of Mg atoms. Most recent works suggest that MgB₂ is a BCS, phonon-mediated superconductor with the two distinct superconducting gaps. In comparison with high-temperature copper-oxide materials, MgB₂ superconductors have more than two times lower anisotropy, significantly larger coherence length, and higher transparency of grain boundaries to the current flow. Thus, they are expected to play an important role in high-current, high-field, large-scale applications.

As the only high-temperature metallic BCS superconductor with very large critical temperature \( T_c \) and the main energy gap at least two times larger than in conventional metallic superconductors, the MgB₂ superconductor is also expected to

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be the material-of-choice for high-performance, ultrafast cryogenic electronics and optoelectronics. MgB$_2$ exhibits high critical current density $j_c$ and in this material, the Cooper pair recombination and electron-phonon interaction times are predicted to be in the single picosecond range. Finally, it is important to mention that MgB$_2$ devices will be able to operate in simple cryocoolers.

The availability of the highest-quality, smooth, and uniform MgB$_2$ superconducting thin films with excellent transport properties is the prerequisite for the realization of any practical cryoelectronic devices. Recently, films with high values of $T_c$ and $j_c$ have been prepared on SrTiO$_3$, Al$_2$O$_3$, Si, SiC, and other substrates by various deposition techniques, including pulsed-laser ablation, thermal co-evaporation, and magnetron sputtering.$^{4,5,6,7,8,9}$ In all the above cases, however, the films required post-annealing at temperatures reaching or above 600°C in either an Ar, vacuum, or Mg-vapor atmosphere in order to form the superconducting MgB$_2$ phase and the properties of the resulting films depended strongly on the conditions of their annealing process. The best reported MgB$_2$ thin films are characterized by $T_c \approx 39$ K and $j_c > 10^7$ A/cm$^2$ at 4.2 K and $5 \times 10^5$ A/cm$^2$ at 30 K.$^{10}$ Preparation of MgB$_2$ thin films using unconventional substrates, such as, stainless steel, glass, or flexible plastic foils is also very attractive. MgB$_2$-on-steel films$^{11}$ are interesting for preparation of low-magnetic shielding and antennas, while most recently obtained MgB$_2$ films on polyamide Kapton-E foils$^{12}$ are unique for their bending, shaping, and cutting abilities.

In this paper, we discuss fabrication of high quality MgB$_2$ thin films and present extensive, time-resolved pump-probe photoresponse studies of the MgB$_2$ films exposed to femtosecond optical pulses. In the following section, we review our growth methods of films deposited on both crystalline and amorphous/plastic substrates by vacuum co-evaporation of B and Mg precursors, followed by high-temperature ex-situ annealing in an Ar or vacuum atmosphere. Section 3 is devoted to a brief overview of the photoresponse mechanisms in superconductors, while Sec. 4 outlines our experimental, all-optical pump-probe measurements. The experimental results are presented in Sec. 5 and Sec. 6 contains the conclusions.

**2. MgB$_2$ THIN-FILM FABRICATION**

Two types of MgB$_2$ superconducting thin films were prepared and investigated, namely, the films on crystalline substrates and on amorphous glass and flexible plastic foils, respectively. In the latter case, we developed a new rapid annealing technique in order to avoid the substrate destruction associated with overheating. In both cases, the obtained films were amorphous with very smooth surfaces, suitable for optical measurements.

**2.1. Amorphous MgB$_2$ Thin Films on Crystalline Substrates**

The precursor Mg-B thin films were prepared by simultaneous evaporation of B and Mg from two separate, resistively-heated Ta and W sources on unheated Si/SiO$_2$, Si/NbN, and Al$_2$O$_3$ (r-sapphire) substrates at p = $8 \times 10^{-4}$ Pa. As it was described in our previous work$^8$, the best superconducting properties of co-evaporated MgB$_2$ films were obtained after ex-situ annealing of the Mg-B precursors for 15 min. in pure Ar at the atmospheric pressure. As is shown in Fig. 1, our films are typically characterized by $T_{c\text{on}}$ of about 33 K and the superconducting transition width $\Delta T_c$ of about 2 K. The highest values $T_{c\text{on}} = 38.2$ K and $\Delta T_c = 0.9$ K were obtained for the MgB$_2$ films deposited on the Si substrate with the 300-nm-thick NbN buffer layer (see Fig. 2).

The films prepared by the Mg-B co-deposition and post-annealed in the Ar atmosphere were amorphous with nanocrystal inclusions (the mean grain size was below 15 nm) and exhibited very smooth surfaces, as illustrated in the Fig. 1 inset, where we show the scanning electron microscope micrographs of post-annealed films. $j_c$ of our films was $>10^6$ A/cm$^2$ at 4.2 K and its temperature dependence indicated a granular, superconductor-normal metal-superconductor (SNS) weak-link composition inside the film.$^{12}$
Fig. 1. Resistance versus temperature dependence and an amorphous, smooth-surface-morphology (inset) of a superconducting MgB$_2$ film, prepared by co-evaporation of B and Mg precursors on a randomly-oriented Al$_2$O$_3$ substrate and post-annealed in an Ar atmosphere.

2.2. MgB$_2$ films on flexible plastic foils

As for the films deposited on amorphous substrates, the Mg-B precursor thin films were deposited by thermal co-evaporation of B and Mg from separate resistive heaters at a vacuum of $8 \times 10^{-4}$ Pa, but this time on flexible, 50-μm-thick polyamide Kapton E foils. The total thickness of Mg-B films varied from 100 to 200 nm after the deposition. They were then ex-situ radiatively annealed in vacuum, using computer-controlled halogen lamps. The annealing temperature could reach 600°C at the Mg-B surface, but at the same time, the foil was kept below 300°C (Kapton deformation temperature) by placing it on an external water-cooled radiator to avoid overheating. No deformation or change of the color of the Kapton E foil was observed after annealing and the resulting MgB$_2$ samples were fully flexible. Time of the annealing process varied from 60 s to 180 s, with the best results obtained for the films preheated at 300°C and only very briefly, for 30 s, heated at 600°C, followed by a 60-s post-heating again at 300°C. The resultant MgB$_2$ films exhibited $T_{\text{con}} = 29.3$ K, $\Delta T_c = 3$ K, and $j_c > 7 \times 10^7$ A/cm$^2$ at 4.2 K. Again, the films were amorphous, according to the x-ray diffraction study, had very smooth morphology, and their $j_c(T)$ indicated granular, SNS-like internal structure. Very similar results were obtained when glass (silica) was used as the substrate.

Figure 2 shows resistive transitions of several our films fabricated on both crystalline and amorphous/plastic substrates. We note that the best properties, as we mentioned in Sec. 2.1, exhibited in the films fabricated on the NbN/Si substrate.

We must stress that our ability to produce high quality MgB$_2$ films on flexible plastic substrates introduces a number of novel aspects to superconducting technology. Films on Kapton E foil substrates can be cut with scissors into desired shapes, such as narrow stripes or large-area magnetic shields. They are unbreakable and can be rolled into small superconducting coils or form flexible microwave or high-speed digital microstrips and coplanar transmission lines. The fabricated films or test structures could be bent multiple times without any observed degradation of their superconducting properties.
Fig. 2. Resistance versus temperature dependences of MgB$_2$ films prepared by co-evaporation of B and Mg precursors on various crystalline and amorphous substrates. The films deposited on the crystalline substrates were annealed at 600°C in Ar, while the films on the plastic foil were treated using the rapid, radiative post-annealing process. Note that the significant drop of the resistance above $T_c$ for an MgB$_2$-on-Si/NbN film can be due to the resistive drop of the NbN buffer layer and not MgB$_2$ itself.

3. PHOTORESPONSE OF SUPERCONDUCTORS

Figure 3 schematically illustrates the dynamics of photon absorption and the subsequent nonequilibrium quasiparticle (QP) relaxation in superconductors. Upon absorption of a light quantum by a Cooper pair [Fig. 3(a)], the highly excited electron, with the energy close to the incident photon energy is created (due to a large physical size [coherence length] of a Cooper pair, only one electron absorbs a photon, while the second one becomes a low-energy QP). Next, this excited (very hot) electron extremely rapidly (on tens of femtosecond time scale) looses its energy via electron-electron (e-e) scattering and creation of secondary excited electrons. In ordinary, in BCS superconductors like Pb or NbN, the above processes continue until the average energy of excited electrons is approximately 0.1 eV (approximately the Debye energy), when the most efficient mechanism for redistribution of energy within the electron subsystem becomes emission of Debye phonons by electrons (e-ph process). The mean free path of those phonons is very small, and they efficiently excite additional electrons (break additional Cooper pairs). As the average energy of electrons in the avalanche decreases towards the energy gap $2\Delta$, the global (effective) electron temperature $T_e$, somewhat above the phonon (lattice) temperature $T_{ph}$ is established. Further cooling of the electron subsystem towards the initial sample temperature $T_s$ is significantly slower and is due to the QP inelastic scattering and recombination processes [Fig. 3(b)].

The QP scattering occurs via the e-ph interaction and can be described by a two-temperature (2-T) model. The time evolutions of $T_e$ and $T_{ph}$ are used as measures of the average energy in the entire system. The balance between $T_e$ and $T_{ph}$ is governed by the set of two coupled differential equations:

$$
\begin{align*}
\frac{dT_e}{dt} &= \frac{\alpha P_{in}(t)}{C_e} - \frac{C_e}{\tau_{e-ph}} (T_e - T_{ph}) \\
\frac{dT_{ph}}{dt} &= \frac{C_{ph}}{\tau_{e-ph}} (T_e - T_{ph}) - \frac{C_{ph}}{\tau_{es}} (T_{ph} - T_e)
\end{align*}
$$

(1)

where $C_e$ and $C_{ph}$ are the electron and phonon specific heats, $\alpha$ is the radiation absorption coefficient, and $V$ is the volume of the superconductor with light illumination. $P_{in}(t)$ is the incident optical power, modeled as a Gaussian-shaped pulse in time domain. The equations also contain the characteristic times $\tau_{e-ph}$ for electron-phonon relaxation, and $\tau_{es}$ for
phonon escape to the substrate. In deriving Eq. (1), we used the energy balance equation \( \tau_{\text{ph}e} = \tau_{\text{ph}e}(C_v/C_{\text{ph}}) \), where \( \tau_{\text{ph}e} \) is phonon-electron scattering time. The 2-T model has been very successfully used to explain both qualitatively and quantitatively the femtosecond pump-probe experiments in normal metals and in superconductors near \( T_c \) and/or in the very weak perturbation regime.

![Fig. 3. Schematics of the photoresponse (QP relaxation) process in a superconductor excited by an optical photon.](image)

The QP recombination into Cooper pairs is associated with emission of phonons with energy greater than or equal to \( 2\Delta \) (so-called \( 2\Delta \) phonons) and is modeled by the set of Rathworh-Taylor (R-T) equations:

\[
\frac{dN_{\text{QP}}}{dt} = I_{\text{QP}} - R N_{\text{QP}}^2 + \frac{2}{\tau_{\text{B}}} N_{\omega}
\]

\[
\frac{dN_{\omega}}{dt} = I_{\omega} + \frac{1}{2} R N_{\omega}^2 - \frac{1}{\tau_{\omega}} N_{\omega} - \frac{1}{\tau_{\omega}} (N_{\omega} - N_{\omegaT}),
\]

(2)

where \( N_{\text{QP}}, N_{\omega} \) and \( N_{\omegaT} \) are the numbers per unit volume of QPs, \( 2\Delta \) phonons, and equilibrium thermal phonons, respectively. \( I_{\text{QP}} \) is the external generation rate (optical pulse) for the QPs, \( I_{\omega} \) represents the \( 2\Delta \) phonons generation rate, \( R \) is the recombination rate for the QPs into Cooper pairs, and \( \tau_{\omega} \) is the phonon pair breaking time. We note that the R-T equations include the reabsorption process (ph-e mechanism), where \( 2\Delta \) phonons break Cooper pairs and generate secondary QPs [Fig. 3 (c)]. Thus, the excited phonons must be actually transferred out of the superconductor and into the outside world (in practice, from the superconducting film to the substrate) in order to complete the relaxation process. The phonon escape [Fig. 3(d)] is a thermal (bolometric) process limited by \( \tau_{\text{es}} \). The R-T equations are nonlinear and best suited to describe nonequilibrium conditions in a superconductor far below \( T_c \) and for moderate to strong external perturbations. They provide a different, but equivalent to 2-T description of the QP dynamics in a perturbed superconductor. In fact, one can note that Eq. (1) can be regarded as a linearized form of Eq. (2), and both approaches coincide under low levels of excitation.
4. EXPERIMENT

Standard femtosecond pump-probe measurements of transient reflectivity change $\Delta R/R$ were performed on our MgB$_2$ thin-film samples. The schematic experimental setup is shown in Fig. 4. The light source was a commercial Ti:Sapphire femtosecond laser, which produced 100-fs-wide pulses at the 800-nm wavelength (1.5 eV) at a repetition rate of 76 MHz. The pump and probe beams are cross polarized to eliminate the coherent artifacts by the interference of the pump and probe beam. The MgB$_2$ samples were mounted on a cold finger in a temperature-controlled, liquid helium continuous-flow optical cryostat, operating down to 3.5 K. Both the pump and probe beams were focused down to <100-μm diameter onto the sample. The pump-probe energy ratio was normally at 10:1. The minimum pump energy per pulse was 13 pJ (1 mW average power) and could be increased by at least two orders of magnitude. The film was fabricated on Al$_2$O$_3$ as mentioned in Sec. 2 with smooth amorphous surface.

![Fig. 4. Experimental setup of the time-resolved pump-probe technique.](image)

In time-resolved pump-probe experiments, the photons from the pump pulse are absorbed in the tested material and create highly excited electrons. According to the photoresponse model presented in Sec. 3, these photoexcited high-energy (hot) electrons thermalize with other electrons “immediately” (on the time duration shorter than the pump pulse width), through the e-e relaxation, followed by slower, but still femtosecond e-ph interaction. In the superconducting state, QPs accumulate above the superconducting gap and we expect to observe a much slower, picosecond, process associated with QP inelastic scattering and Cooper pair recombination. Finally, our signal should follow the nanosecond, bolometric lattice cooling process. The $\Delta R$ signal, induced by the pump, is measured by the probe beam time-delayed with respect to the pump. Thus, by studying $\Delta R$ as a function of the time delay between the pump and probe beams, the time-resolved relaxation process of excited carriers can be measured directly. Under weak perturbations, which apply to most of our experiments, the 2-T model is applicable, $T_e$ is only several K above $T_{ph}$, and $\Delta R$ is approximately a linear function of $T_e$.

Figure 5 shows the room-temperature photoresponse signal of a test sample at an average pump energy of 0.13 nJ (10 mW). The fit assumes a single exponential decay of the relaxation process and corresponds to the solution of the following (simplified 2-T model) differential equation:

$$\frac{d(\Delta R/R)}{dt} = I(t) - \frac{\Delta R/R}{\tau_R},$$

where $I(t) = I_0 \exp(-4 \ln 2 t^2/\tau_p^2)$ is a Gaussian-shape excitation due to the laser pulse with FWHM of $\tau_p$. $\tau_R$ is the single-exponential relaxation rate. The solution of Eq. (3) is in the form:
\[ \Delta R / R = C_0 \left[ 1 - \operatorname{erf} \left( \frac{t_r}{3.62 \tau_R} \right) - \frac{1.81 t_r}{t_r} \right] \exp \left( - \frac{t}{\tau_R} \right), \]  

where \( \operatorname{erf}(x) \) is the error function, \( t_r \) is the 10%–90% risetime of the experimental signal, and \( C_0 \) is the normalization constant. Since the probe pulse has a certain pulsewidth, the measured signal would be a convolution of the response signal and the probe pulse, causing a broadening of \( t_r \). \( t_r \) also accounts for any other broadening effects. The fit in Fig. 5 gives \( t_r \approx 300 \) fs and \( \tau_R \approx 160 \) fs, although at the end of the relaxation process, there is a small portion of the curve that follows a much longer decay. The dash line in Fig. 5 gives the cross-correlation of the pump and probe beams, which can be regarded as the intrinsic response of our pump-probe system. As we can see, both \( t_r \) and \( \tau_R \) of \( \Delta R / R \) are somewhat longer, but comparable to the cross-correlation function, which means that in our measurements, we are at the experimental system limit and we cannot directly measure the intrinsic values of \( t_r \) and \( \tau_R \). In our measurements, we do not see any noticeable change of \( t_r \) with temperature or pump fluence.

![Room-temperature photoresponse of a MgB_2 thin film (solid squares) and the fit (thin line) based on Eq. (4). The dashed line shows the cross-correlation signal of the pump and probe beams.](image)

5. EXPERIMENTAL RESULTS

There were no temperature or pump intensity dependence at room temperature. However when the MgB_2 samples were cooled to low temperatures, starting below 60 K, the \( \Delta R / R \) photoresponse signal exhibited an additional slow component that followed the dominant femtosecond relaxation process observed at room temperature. The slow component became more pronounced with decreasing of the temperature and decreasing of the pump intensity. The pump intensity dependence and the relaxation time constant change at low temperature have been reported in several pump-probe measurements in high temperature cuprates as well.\(^\text{18,19,20}\) Figure 6 shows the photoresponse at 5 K (nominal temperature) for different values of the pump intensity. At the lowest pump level, the relaxation is mainly characterized by the long, picosecond-range process. With increasing of the pump intensity, the initial fast relaxation started to show up and the response became bi-exponential.

Part of the reason for the intensity dependence of \( \Delta R / R \) might due to laser heating of our sample. At room temperature, the specific heat is very large and the ambient temperature is high enough to ignore the heating. At low temperatures, the heating has both a steady-state (averaged laser heating) and transient (single pump pulse heating) components.\(^\text{18}\) The steady-state heating, measured by the change of the sample \( T_c \), with and without incident laser radiation, gave the constant temperature shift of about 0.8 K/mW around \( T_c \). The transient heating can be estimated by:\(^\text{21}\)

\[ \Delta T = \frac{\Delta W}{mC}, \]
where $\Delta W$ is the single pulse energy, $C$ is the specific heat, and $m$ is the mass of the illuminated volume. Since $C$ is very small near 4 K, the transient heating cannot be ignored at very low temperatures. A rough estimate gives about 14 K increase at 4 K and 2 K increase at 20 K by the 2-mW pump pulse. (based on the parameters from ref. 17) Thus, it is extremely difficult to measure the intrinsic (not pump power affected) photoresponse at very low temperatures. On the other hand, above 20 K, transient heating by the pump beam can be neglected.

As shown in Fig 7, different bias currents also changed significantly the relaxation process when above the critical current. The film critical current at 3.5 K with the 0.13 nJ (10 mW) pump illuminating the sample was around 8 mA. By current biasing the MgB$_2$ film into the normal state, we got the suppression of the slow photoresponse component. When the bias of the film was even further increased, we observed that the $\Delta R/R$ response became negative after the picosecond response, apparently, due to the resistive heating of the film, since the same negative signal, without the slow component, was also observed when the pump intensity was very high. On the other hand, when the biasing current was below the critical current there were no noticeable changes in the $\Delta R/R$ photoresponse and the slow component was present.

When investigating the temperature-dependent properties of the $\Delta R/R$ signal, it is crucial to determine the actual temperature of the studied film. In order to minimize the heating due to the pump pulse and yet still achieve an acceptable signal-to-noise ratio, all our measurements were made with an average pump intensity of 26 pJ (2 mW) and the pump spot size of $\sim$100 $\mu$m diameter. These conditions corresponded to the pump energy density of $3.3 \times 10^{-7}$ J/cm$^2$. 

![Fig. 6. Photoresponse at 5 K (nominal temperature) for different values of the pump power.](image)

![Fig. 7. Transient photoresponse at 3.5 K (nominal temperature) and the 10-mW pump power. The film was biased at different current levels.](image)
Figure 8 shows the $\Delta R/R$ response at different temperatures. To present the results in a clear manner, all the curves shown in Fig. 8 are the fitted curves of the original signals, based on the model presented in Sec. 4. To account for the bi-exponential relaxation process, two different relaxation time constants were employed. Each of them followed Eq. (4) and they were added up together. In addition, the bolometric process which accounts for the change of the background level was treated as a constant shift within picosecond range. Figure 8(b) shows the same data as Fig. 8(a), but in a semi-log scale to emphasize the bi-exponential behavior. We note that the slow component becomes shorter and less dominant with the increase of temperature. At 60 K, the slow relaxation disappears and the entire relaxation process is essentially the same as the room temperature photoresponse. On the other hand, in the temperature range between 4 K and 10 K the $\Delta R/R$ signal saturates. This could be associated with the superconductor energy gap saturation at very low temperatures, however, we cannot exclude that the saturation is due to the heating by the pump laser, as discussed above.

![Figure 8](image.png)

Fig. 8. Normalized $\Delta R/R$ photoresponses (only fits to actual data are shown), measured at different temperatures and presented in the linear (a) and semi-log (b) scales.

Figure 9(a) shows the $\Delta R/R$ amplitude versus temperature for a sample, with the film thickness of less than 60 nm, so the heating effect should be minimized. In contrast to most of the pump-probe results obtained on high-$T_c$ oxide superconductors, in our case the $\Delta R/R$ amplitude decreases below $T_c$. However, since we have obviously two different relaxation processes, it would be of interest to see the relative contribution from each process. Figure 9(b) shows the ratio of the amplitude due to the slow process divided by the total amplitude. It is clear that at very low temperatures the slow relaxation process is dominant and rapidly gets weaker as temperature increases, finally vanishing in the noise floor near 60 K.

![Figure 9](image.png)

Fig. 9. The total $\Delta R/R$ amplitude (a) and the slow component amplitude normalized to the total $\Delta R/R$ (b) versus temperature
Figure 10 presents the fitted time constants of both the fast and the slow relaxation processes as a function of temperature. The fast relaxation time constant [Fig. 10(a)] slowly increases until 40 K and saturates. On the other hand, the slow relaxation time constant decreases with the temperature increase and exhibits a discontinuity in the 25 K to 30 K range, which corresponds to the critical temperature of our film. Above $T_c$, it remains constant up to ~40 K and drops into the noise level (the amplitude of the slow component becomes so small that it is very difficult to measure and fit it accurately) at 60 K. Compare to the low fluence pump-probe measurements on high-temperature cuprates, the relaxation time change in MgB$_2$ thin film is not as significant and does not follow a $T^{-3}$ tendency.\textsuperscript{19,20}

![Figure 10](image)

Fig. 10. The fast component (a) and the slow component (b) relaxation time constants versus temperature.

6. CONCLUSIONS

We have reviewed fabrication techniques leading to the growth of superconducting MgB$_2$ thin films on different substrates and presented our initial studies on the time-resolved carrier dynamics in this new, metallic high-temperature superconducting material. The films were deposited on both crystalline and amorphous (plastic) substrates and post-annealed at high temperatures, resulting in the amorphous phase samples with very smooth surface morphology and good superconducting properties. Femtosecond pump-probe studies allowed us to observe the bi-exponential photoresponse on the MgB$_2$ films at temperatures below 60 K. The fast, femtosecond component had the same characteristics as the single-exponential signal at room temperature and we associate it with thermalization of optically excited electrons. On the other hand, the slow, picosecond component, which existed only at low temperatures and only when our films were current-biased below their critical current, we tentatively interpret as the dynamics of Cooper pairs. The fact that the slow-component signal also exists above $T_c$ is, in our opinion, an indication of the presence of superconducting fluctuations in our MgB$_2$ films.

Experimentally observed single-picosecond photoresponse signal of MgB$_2$ shows that this material is a very good candidate for ultrafast superconducting electronics and optoelectronics. We expect that, similarly to NbN, thin-film MgB$_2$ photodetectors will be able to operate as efficient photon counters with counting rates exceeding 100 GHz.
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