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Developing Quantum Levitation of ICF Capsules Coated with MgB2 Thin Films

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Developing Quantum Levitation of ICF Capsules Coated with MgB_2 Thin Films

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ABSTRACT

Current inertial confinement fusion (ICF) capsule support technologies create implosion perturbations which reduce fusion yield, driving the search for new support paradigms. Quantum levitation of the capsule will eliminate the requirement of a physical support structure, increasing fusion yield. The application of an external magnetic field to a capsule coated with a superconducting film can provide the necessary conditions for levitation. Magnesium diboride (MgB_2) is an attractive option for ICF applications as it has a high reported superconducting transition temperature of 39 K and is a low Z compound. This project is part of an ongoing effort which seeks to coat ICF capsules with a thin layer of superconducting MgB_2. This project studied the synthesis of MgB_2 and diffusion/reaction kinetics of B/Mg/B multilayer thin films. These films were sputter deposited on flat glassy carbon substrates. Films were annealed in a tube furnace at temperatures between 400˚C and 650˚C for a total of 29 hours with film characterization done at predetermined intervals. At each interval, superconducting properties of the samples were evaluated with superconducting quantum interference device (SQUID) magnetometry, while Rutherford backscattering (RBS) with 2 MeV $^4He^+$ ions was done to determine the composition and depth profile of the films. Scanning electron microscopy (SEM) and atomic force microscopy (AFM) were used to characterize surface morphology. Superconducting behavior was observed in thin films annealed at and above 450˚C. Formation of superconducting MgB_2 at 450˚C has not been previously reported below 500˚C. The surface of the samples annealed at 500˚C and below was smooth with a measured roughness of ~3 nm. After 29 hours of annealing time, the 450˚C sample had a transition temperature of 27.3 K. The highest transition temperature measured was 30.9 K and was associated with a sample annealed for 29 hours at 650˚C. Transition temperatures were weakly positively correlated with annealing temperature and showed dependence on initial structural quality and oxygen contamination. Current research is attempting to synthesize superconducting MgB_2 coatings on spherical Si beads with the findings of this study. Future efforts are focused on the construction and testing of a levitation apparatus.

1. INTRODUCTION

Magnesium diboride (MgB_2) is a versatile superconductor due to its relatively high transition temperature (T_c) of 39 K, as well as its high critical current densities and high critical magnetic fields. MgB_2 is also relatively easy to synthesize. It can be utilized in a variety of structures including wires and thin films [1, 2]. A potential use for MgB_2 as a thin film includes the levitation of inertial confinement fusion (ICF) fuel capsules. This potential application acts as the primary motivation for this project. Levitation in an external magnetic field would require a smooth thin film coating of MgB_2 on the outermost surface of an ICF capsule.

Conceptually, levitating an ICF capsule coated with superconducting film could simply be accomplished through the presence of an electromagnet or permanent magnet located outside of the hohlraum, in the case of indirect drive fusion. Superconductors, in this case MgB_2, act as perfect diamagnets which expel magnetic flux due to the Meissner effect. This expulsion of flux forces the external magnetic field lines to flow around the outer surface of the capsule. This results in a Lorentz force which can counter the gravitational force acting on the capsule [3]. While avoiding detailing the intricacies of levitation, this paper includes an example that demonstrates the relative key parameters involved. Our simulation shows that an ~2 mm diameter capsule weighing ~7-12 mg that is coated with an ~40-400 nm thick MgB_2 outermost layer could be levitated 5-6 mm in height above a magnet providing a 10-30 mT field and a current density of 10-1000 A cm^{-2} at the bottom of the capsule. This could result in a Lorentz force of 50-150 μN. The successful integration of a quantum levitation-based approach would remove the necessity of a physical support system, such as tents or poles, and provide a solution to the implosion perturbation which currently limits ICF implosion yields [4, 5, 6].

Here, non-epitaxial MgB_2 films were synthesized on flat glassy carbon substrates by annealing a sputter deposited B/Mg/B multilayer structure in temperatures chosen to maintain the solid-state regime. Glassy carbon substrates were used to represent the carbon-based capsules used in ICF applications. Sputter deposition was chosen as it can eventually be used to deposit on non-planar surfaces. Elemental composition, annealing temperature, and the development of superconducting properties are the focus of this endeavor.

2. EXPERIMENT

MgB_2 thin films were made by thermally processing B/Mg/B multilayer structures that were annealed at temperatures below the melting point of magnesium. The annealing process promoted the solid-state inter-diffusion of Mg and B, accompanied by the $\mathrm{Mg} + 2\mathrm{B} \rightarrow \mathrm{MgB_2}$ reaction. The multilayer structures were sputter deposited onto ultra-densified amorphous carbon (UDAC) substrates in an Ar atmosphere. The target thicknesses of the multilayers were ~35/15/35 nm, with the glassy carbon substrate being 0.635 mm thick.

Before annealing, samples were placed in Ta Tubes (Eagle Alloys Corp., 99.95% purity; an inner diameter of 10 mm and a length of ~50 mm). This tube also contained ~100 mg of Mg (American Elements, 99.9% purity) to account for possible Mg vapor pressures present at higher temperatures. The tube was then crimped while containing an N_2 atmosphere. The sealed Ta tubes were then annealed in a 50 mm diameter quartz tube furnace under flowing Ar. Samples were annealed at temperatures between 400 ˚C and 650 ˚C, with a heating and cooling ramp rate of 10 ˚C. Annealing time for each sample totaled 29 hours, with cessation of annealing done at 1, 4, 9, 19, and 29 hours for characterizing the films.

The depth profile of the elemental composition of the samples was measured both before and during the annealing sequence. This was done using Rutherford backscattering spectrometry (RBS) with a 2 MeV $^4He^+$ ion beam. RBS is a nondestructive high-energy ion scattering based method which provides a depth-resolved analysis of the elemental composition of near surface layers [7, 8]. During RBS, the He beam was incident normal to the surface of the sample with a backscatter detector positioned at ~165 degrees relative to the direction of beam incidence. The surface morphology of the films was determined with scanning electron microscopy (SEM) and atomic force microscopy (AFM).

Superconducting properties were measured using a Quantum Design MPMSXL SQUID magnetometer. Magnetic moment (*M(T)*) was measured at 100 Oe over the temperature range of 5-50 K. Samples were mounted with the film surface parallel to the applied magnetic field and zero field cooled to 5 K before measurements were taken.

3. RESULTS

Studies of the formation of MgB_2 at various annealing temperatures with the multilayer deposition method were performed. A study of the solid-state diffusion couple of Mg and B was also done. RBS was used to observe the diffusion of Mg into the surrounding B layers.

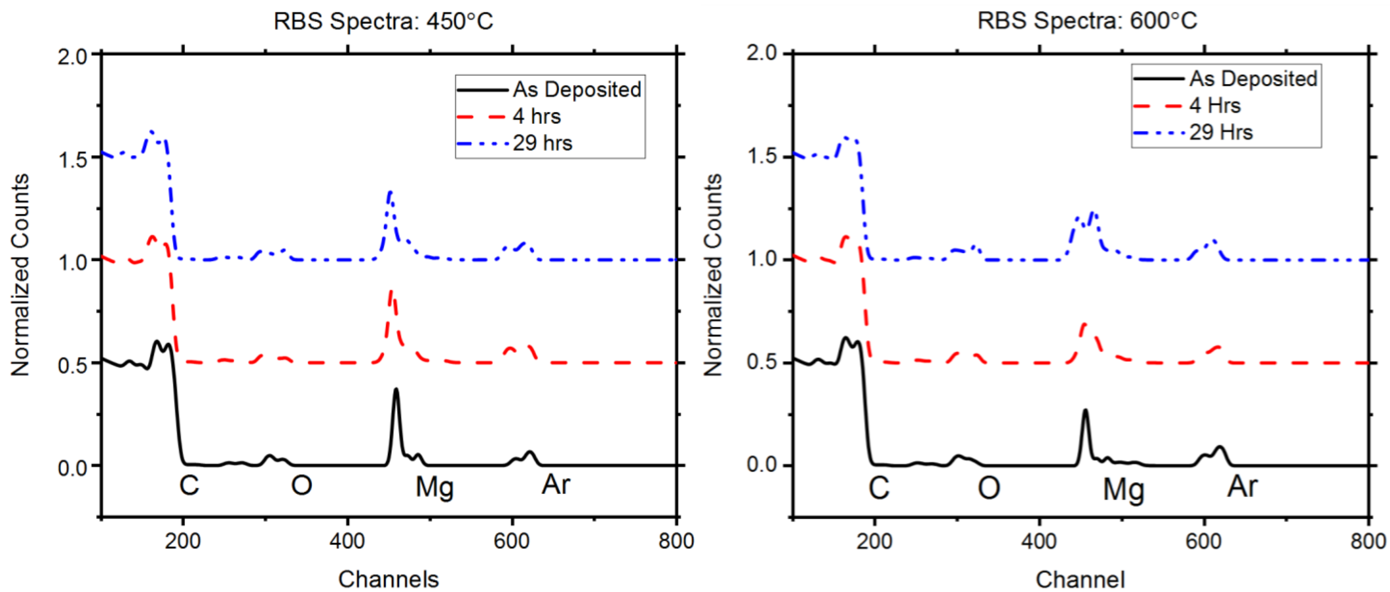


Figure 1: RBS simulated fit spectra showing the evolution of two samples with annealing. The plot on the left shows the evolution of a sample annealed at 450˚C. The plot on the right represents a sample annealed at 600˚C.

Figure 1 shows RBS spectra that represent the general trends observed in the samples. The 600˚C sample (shown on the right) is characterized by the Mg peak shrinking in height and becoming wider, with the eventual formation of a double peak at 29 hours of anneal time. This peak shifting indicates the substantial diffusion of Mg into the surrounding B layers. The right-most Mg peak also suggests the formation of MgO on the surface of the samples. This double-peaking trend was observed in samples annealed at and above 525˚C. A 450˚C sample (left) shows significantly less peak broadening as the sample is annealed. This indicates that Mg diffusion at lower temperatures is minimal. This behavior was observed in samples annealed at and below 500˚C.

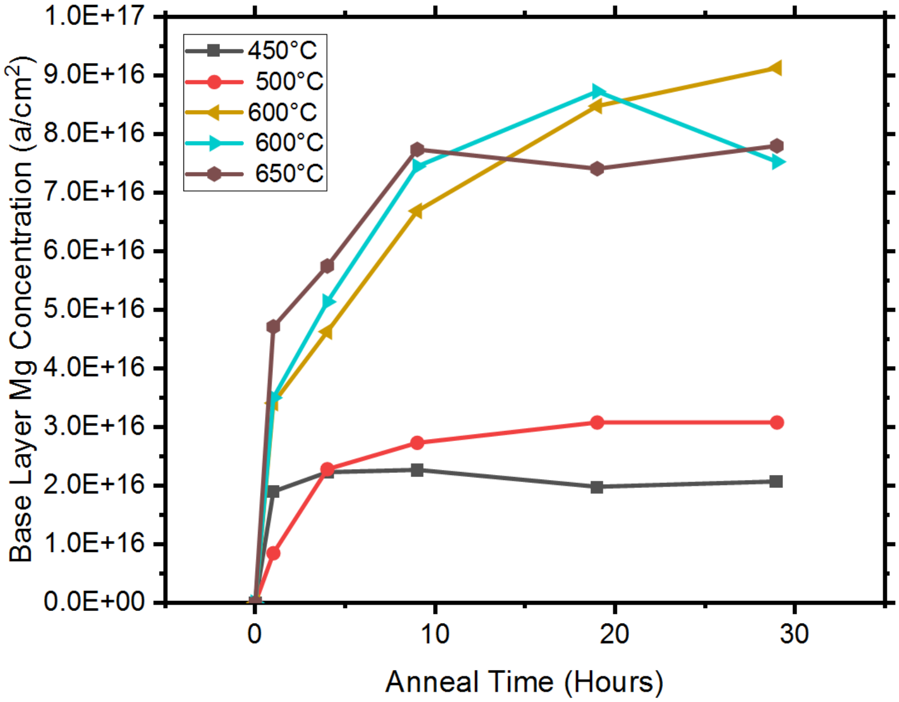


Figure 2: Mg concentration in the B layer (referred to as "the base layer") contacting the C substrate. Concentration data derived from RUMP simulations fitted to collected RBS spectra. Concentration is denoted in atoms/cm^2, or areal density.

Figure 2 shows that Mg diffusion into the base layer of B is dependent on the annealing temperature of the sample. Higher temperature samples (≥600˚C) showed significant diffusion of Mg. At these higher temperatures, Mg diffusion continued as anneal time increased. This behavior was not observed in lower temperature samples (≤500˚C), in which appreciable Mg diffusion stops within the first 4 hours of annealing.

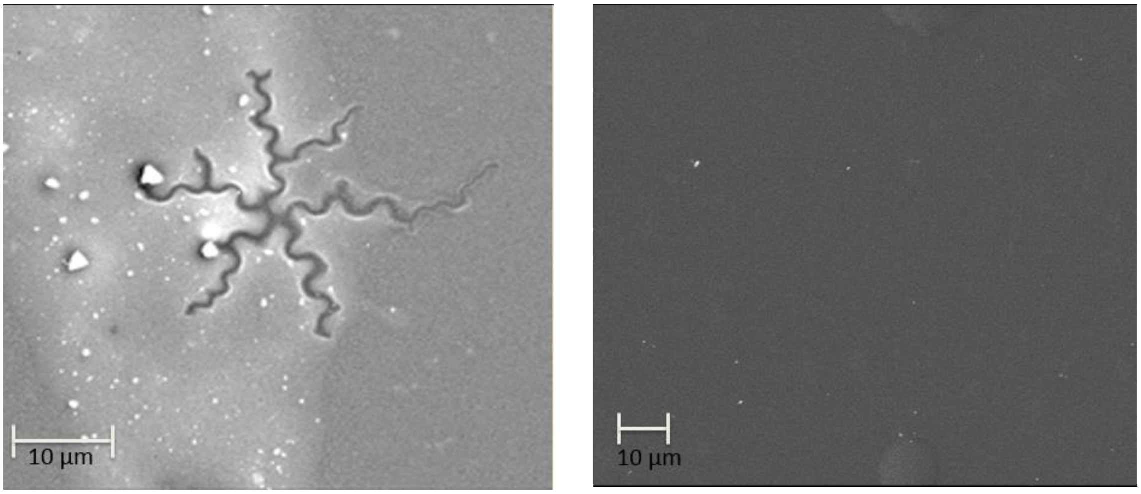
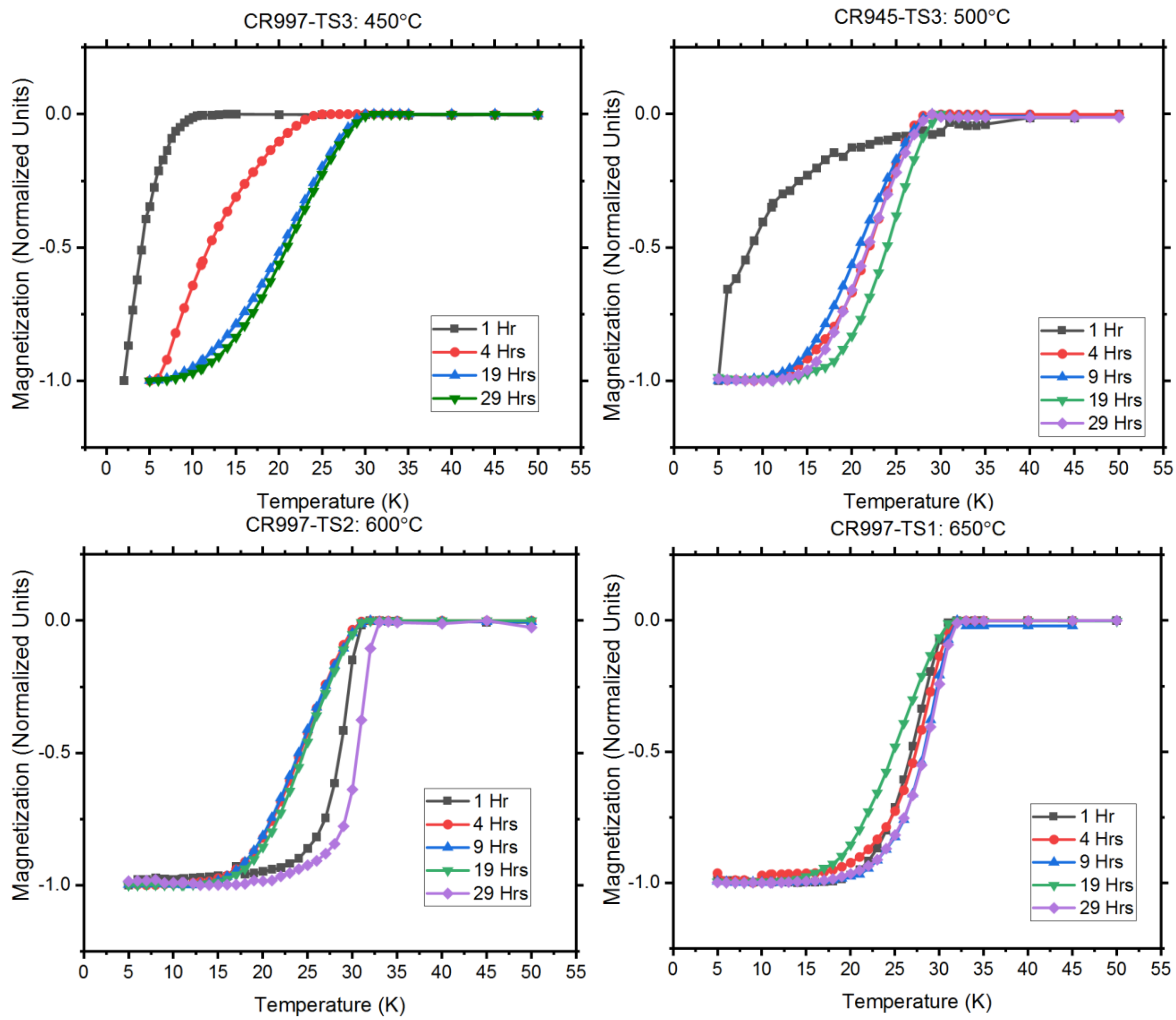


Figure 3: SEM of two samples annealed at different temperatures. The image on the left represents a sample annealed at 600˚C. The image on the right represents a sample annealed at 500˚C.

Figure 3 displays SEM images of two samples annealed at different temperatures. The sample on the right was annealed at 600˚C. It displays cracking and rough surface. This morphology is characteristic to samples annealed above 500˚C. The image on the right represents



a sample annealed at 500˚C and does not display cracking. This sample was relatively smooth with a measured roughness of ~3 nm.

Figure 4: A collection of plots showing normalized magnetic responses on the y-axis. For the purposes of this report, the magnitudes of the magnetization responses are not provided. The superconducting transition behavior is being examined on a relative basis, with a sharper s-curve denoting a faster transition. For this report, the transition temperature is defined as the 90% point on the transitory curve, moving from left to right.

Figure 4 shows a collection of magnetic response plots. At 450°C, superconducting behavior does not become apparent until at least 19 hours of annealing have been completed. Higher temperature plots indicate that superconducting MgB_2 is formed within the first hour of annealing.

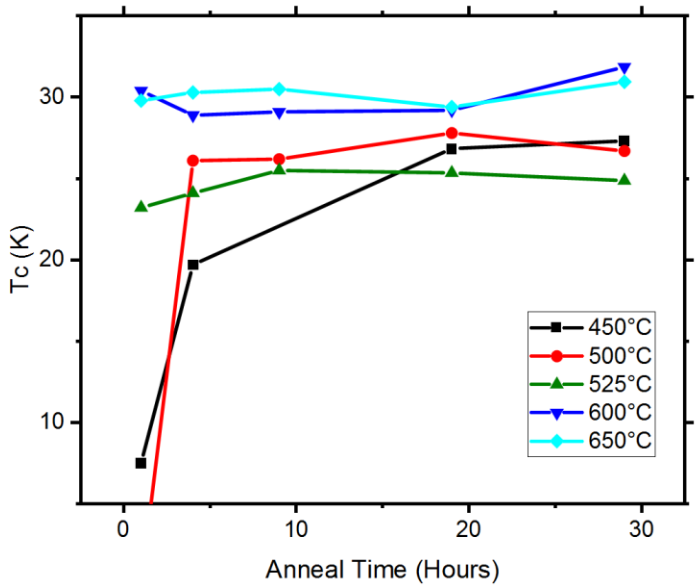


Figure 5: Superconducting transition temperatures plotted as a function of annealing time. Transition temperatures were determined using the method described in Figure 4.

Figure 5 shows that transition temperature remains relatively constant for samples annealed at temperatures ≥600°C. These samples also had the highest transition temperatures of ~29 K. For the samples annealed at 500°C and 525°C, their transition temperatures (~25 K) were consistently lower than the samples annealed at higher temperature. The sample annealed at 450°C shows an increasing transition temperature with annealing time.

4. CONCLUSION

We have demonstrated the formation of superconducting MgB_2 in B/Mg/B multilayers across a range of temperatures. Samples annealed at 450°C yielded superconducting MgB_2, but the transition temperatures were not comparable to those of other samples until higher annealing times had been reached. The highest transition temperatures were observed in samples annealed at temperatures ≥ 600°C. The samples annealed at lower temperatures (≥ 500°C) had relatively smooth surfaces, which would be ideal for the intended ICF capsule coatings. Future research into the synthesis of MgB_2 on spherical substrates will be performed using the methods developed in this study.

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