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Project Number: 14-2098
Project Title: Magnetic Nitride Films for Superconducting Memory Devices
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Abstract: This work investigated pulsed laser deposition of Cr-doped AlN thin films for use as ferromagnetic layers in memory cells for superconducting electronics. The film morphology, crystalline structure, and magnetization were investigated as a function of laser fluence on the target and background N_2 pressure during deposition. Higher laser fluence resulted in films composed of a smooth underlayer with a high density of poorly adhered, rough crystallites at the surface. Lower laser fluence reduced the density of surface crystallites significantly. X-ray diffraction showed that films grown at high laser fluence show crystalline peaks associated with AlN. Both types of films showed hysteretic magnetization curves consistent with films grown by other deposition techniques.

Introduction: Superconducting Electronics (SCE) is one of the leading technology candidates for high performance, ultra-low power computation needed to address our society's needs. Although high-speed, digital superconducting circuits has been demonstrated, the promise of extending these devices to high performance computing has been severely hindered by the lack of a fast, low energy, high capacity, integrated memory cell and scalable 3D architecture. Recently, ideas for manipulating the critical current of Josephson junctions (JJ) using magnetic interlayers have been proposed. The magnetization of a ferromagnetic layer can be set to control the magnitude of the junction critical current, resulting in two distinct states representing a "O" or "1". Such cells could then be used as a fully-integrated, energy-efficient, scalable, non-volatile RAM. Identifying and demonstrating a ferromagnetic layer that can be switched at high speeds with low power is critical for this technology. This work investigates magnetic nitride thin films to address this issue. Although Chromium-doped Aluminum Nitride (AlN) and Galium Nitride films have promising ferromagnetic properties, their incorporation into a switchable memory device has never been attempted. We used pulsed laser deposition to fabricate these films under conditions and at temperatures compatible with incorporation into superconducting electronic structures and measured their surface morphology, crystalline structure, and magnetic properties in order to assess their performance for future memory cells.

Detailed Description of Experiment/Method: Films were grown by ablating a commercial target (96% AlN, 4% Cr) using an excimer laser operating at 248 nm. The energy density was adjusted to either 0.5 J/cm2 (low fluence) or 1.2 J/cm2 (high fluence). The SiO2/Si substrates were placed 10 cm away from the target and heated to 600°C. The N_2 gas pressure was fixed at 30-50 mTorr during deposition. The film morphology was characterized using a FEI Nano Nova 200 field emission scanning electron microscope. The crystal structure of the films was investigated by x-ray diffraction using a Philips X-pert MRD. Magnetization measurements were performed in a commercial Quantum Design MPMS system.

Results: The commercial Cr:AlN target, purchased from ACI Alloys, was considerably more fragile and porous than the oxide targets they have provided for us in the past. In fact, when mounting the target in the deposition chamber, small flakes were visibly seen to adhere to anything that touched the surface of the target.

Ablation at high laser fluence resulted in a "powdery" coating on the substrates and the surfaces inside the deposition chamber, indicating that the target was not ablating uniformly. Figure 1 (a,b) shows the SEM images of the morphology of films grown at high laser fluence. The surface is covered with 1-20 µm diameter crystallites (a) above a smooth background film (b). Energy dispersive spectroscopy (EDS) measurements on individual crystallites (Figure 1c) show significantly excess Al content from what would be expected for stoichiometric AlN. X-ray diffraction scans (Figure 2) show peaks consistent with both polycrystalline Al and AlN. Magnetization measurements performed at room temperature (Figure 3) show a hysteresis loop consistent with what has been reported in the literature for Cr:AlN thin films grown by other deposition techniques.

Films grown at lower fluence show a much lower density of crystallites (Figure 4a) but the same smooth background as seen in Figure 1c. EDS (Figure 4b) shows much lower intensity Al and N peaks associated with the thin, smooth background film. X-ray diffraction measurements on the films grown at lower fluence do not show any well-defined crystalline peaks. The hysteresis loops (Figure 5) are very similar to those measured for films grown at high fluence.

Discussion: This work shows that ferromagnetic Cr:AlN films can be grown by pulsed laser deposition. The clear difference between low and high laser fluence for film surface morphology and x-ray diffraction spectra suggests that for this porous, fragile Cr:AlN target, high laser fluence produces large crystallite ejecta in addition to congruent ablation of the target species. The similarity in the magnetization for both low and high laser fluence indicates that the smooth background film comprises Cr:AlN, as AlN is not ferromagnetic. The morphology of the smooth background films is exactly what is needed for the ferromagnetic layers in multilayer superconducting memory cells.

Impact: This proposal contributes to DOE's mission to enhance U.S. security and economic growth through transformative science, technology innovation, and market solutions to meet our energy and environmental challenges by providing a technological path to enable energy-efficient high-performance computation. It also benefits other federal agencies (such as DHS and NSA) with needs for low-power, energy-efficient, high-performance computing to ensure national security. Further work is needed to optimize growth of this layer to completely eliminate surface crystallites so that these films can be incorporated into a device. It is expected that improving the density of the target will be critical. Once the film growth has been optimized, the magnetic properties will be tailored by varying the Cr content to minimize the switching energy. These next steps will be performed as part of a follow-on LDRD that starts in FY15.

Conclusion: This work established that ferromagnetic Cr:AlN films could be grown by pulsed laser deposition. Future work will be needed to optimize film growth and more fully characterize the magnetic properties before incorporating these films into superconducting memory devices.

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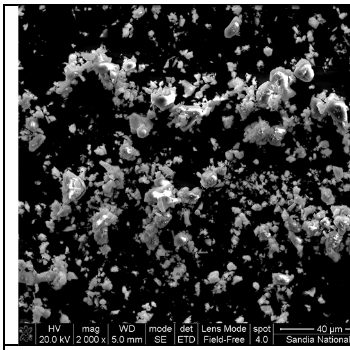

Figure 1a: SEM image showing high laser fluence produces films with a high density of surface crystallites.

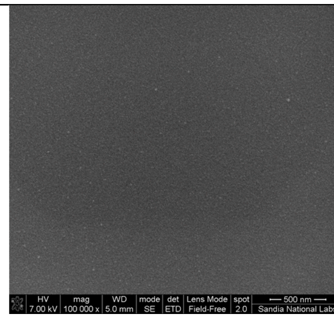

Figure 1b: SEM image shows films grown at high laser fluence have a smooth background layer beneath the surface crystallites.

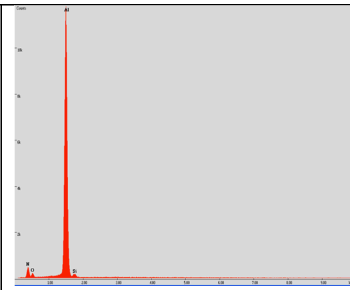

Figure 1c: Energy dispersive spectroscopy scan showing Al and N.

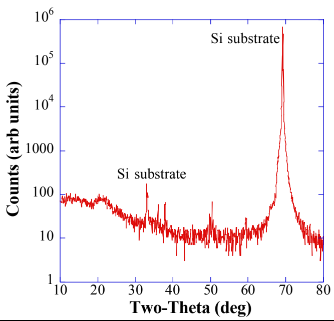

Figure 2: X-ray diffraction scan showing polycrystalline Al and AlN

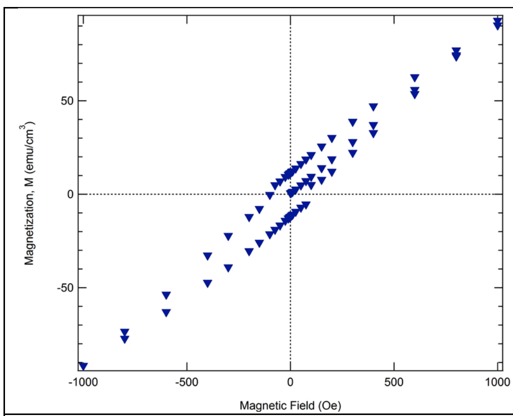

Figure 3: Hysteresis loop showing ferromagnetic behavior for film grown at high laser fluence.

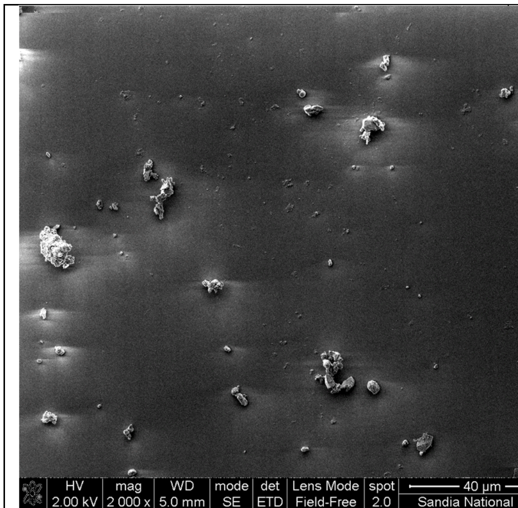

Figure 4a: SEM image showing much lower surface crystallite density for films grown at low laser fluence.

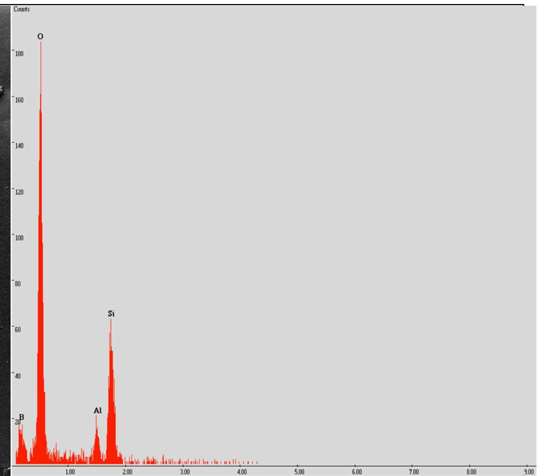

Figure 4b: Energy dispersive spectrum showing much weaker Al and N signals associated with smooth background film.

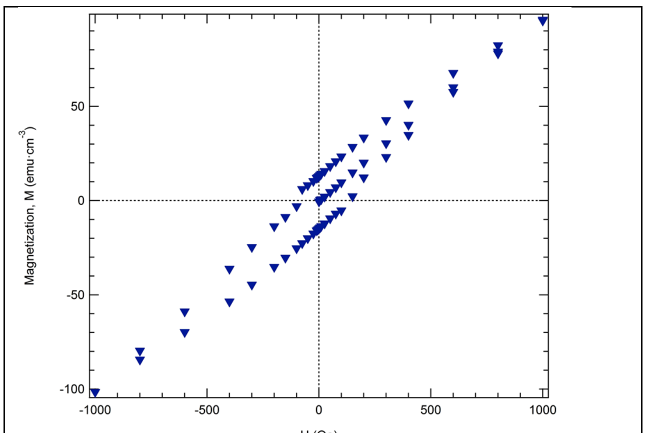

Figure 5: Hysteresis loop showing ferromagnetic behavior for film grown at low laser fluence.