Wednesday Afternoon, August 7, 2024

ALD Fundamentals
Room Hall 3F - Session AF3-WeA
Growth and Characterization: Plasma Enhanced ALD II

Moderators: Prof. Matti Putkonen, University of Helsinki, Dr. Mikko Söderlund,, Beneq Oy

4:00pm **AF3-WeA-11 UHP PEALD Growth and High Field Dielectric Testing of κ-Ga_2O_3 Films***, **Bangzhi Liu,*** The Pennsylvania State University

[1]Bangzhi Liu, [1]Yeseul Choi, [1]Smitha Shetty, [2]Gilbert B. Rayner, [1]Fan He, [3]Kunyao Jiang, [1]Benjamin L. Aronson, [3]Jingyu Tang, [4]Yongtao Liu, [4]Kyle P. Kelley, [3,5]Jr.; Robert F. Davis, [3]Lisa M. Porter, [1,6]Susan Trolier-McKinstry

1. Materials Research Institute, Penn State University; 2. The Kurt J. Lesker Company; 3. Materials Science and Engineering, Carnegie Mellon University; 4. Oak Ridge National Laboratory; 5. Electrical and Computer Engineering, Carnegie Mellon University; 6. Materials Science and Engineering, Penn State University

Ga_2O_3 has multiple different polymorphs: α-, β-, γ-, and ε(κ)-phases. β-Ga_2O_3 has drawn significant attention in the power electronics community since it is an ultra-wide bandgap semiconductor and, fortunately, the only thermodynamically stable phase. The ε (also called κ)-phase is the next most stable polymorph. This metastable phase has been predicted to be ferroelectric[1,2] and can be a suitable candidate for non-volatile memory applications if its ferroelectricity is confirmed. Technically, using ALD to grow this film is ideal for memory device fabrication, given its precise thickness control and excellent conformality.

To this end, we invested significant effort in developing a Plasma-Enhanced ALD (PEALD) process to grow κ-phase with c-orientation on a conductive substrate for electrical testing. The deposition system used was a KJ Lesker ALD150LX operating under ultrahigh purity (UHP) conditions. A major challenge was to find conditions that favor the formation of metastable κ-phase while suppressing the growth of stable β-phase. By controlling O_2 flow, vacuum level, plasma power, growth temperature and substrate type, we successfully grew c-oriented κ-phase (50 nm thick) on platinized sapphire substrates. The films were characterized by ellipsometry, FESEM, XRD, and ToF SIMS for material properties and by high field dielectric testing and Piezoresponse force microscopy for the possible ferroelectric properties. A comparison was made to Metal-Organic Chemical Vapor Deposition (MOCVD) grown thick films (700 nm) with predominantly the κ-phase prepared by our collaborators in parallel to better evaluate the ferroelectricity of κ-Ga_2O_3[3].

4:15pm **AF3-WeA-12 Crystalline Phase Control of Manganese Oxide Films by Plasma Enhanced Atomic Layer Deposition***, **Zhongwei Liu,** J. Ren, H. Fang, L. Sang,* Beijing Institute of Graphic Communication, China

Over the past decades, manganese oxides have attracted increasing interests due to their various compositions, such as MnO, Mn2O3, MnO2, Mn3O4, and Mn5O8, in which several oxidation states, +2, +3, and +4 exist. The multitude of structures and valence state offer a number of applications for manganese oxides in catalysis, microelectronic, biosensors, and Li ion battery. In this work, we developed a plasma enhanced pulsed chemical vapor deposition process for manganese oxide (MnOx) thin films using bis(1,4-di-tert-butyl-1,3-diazabutadienyl)manganese(II) (Mn(dad)2) as the Mn precursor. Mn(dad)2 is an active compound with high volatility, and suitable for CVD or ALD process. MnOx film was characterized by X-ray photoelectron spectroscopy (XPS), X-ray diffraction (XRD), scanning electron microscopy (SEM) (FEI Talos F200S). The effects of the deposition temperature and the types gases, such as H2, Ar, H2 plasma and Ar plasma, on phase composition of manganese oxides were carefully investigated. When Ar or H2 gas was employed as the discharge gas and the deposition temperature was 120 C, amorphous or nanocrystalline MnOx was obtained. In contrast, the film grown in Ar plasma was a face-centered cubic (fcc) MnO structure. In the case of H2 plasma, the diffraction peaks can also be indexed to fcc MnO, except that the preferred orientation of the film was different. As the deposition temperature was increased to 180 C, the film deposited in Ar or H2 gas showed Mn3O4 structure. Similar to that grown at 120 C, the film deposited at 180 C in Ar or H2 plasma was identified to be MnO, indicating that the deposition temperature has negligible effect on the film crystallinity under plasma condition. If the deposition temperature was further raised to 240 C, a mixture MnO and Mn3O4 was obtained for the films grown in Ar or H2 gas, while in the case of Ar or H2 plasma, the afforded film is still MnO. These results indicated that the plasma had a significant effect on MOx crystalline phase.

4:30pm **AF3-WeA-13 Superconducting Ultrathin Niobium Nitride Films for Quantum Application***, **Mario Ziegler,** E. Knehr, E. Mutsenik, S. Linzen, G. Oeslner, E. Il'Ichev, R. Stolz,* Leibniz Inst. of Photonic Technology, Germany

Superconducting thin films are the basis for a wide range of applications such as quantum cryptography, sensing, quantum metrology or quantum computing. On one hand, devices such as superconducting nanowire single photon detectors (SNSPDs) are in need for high-quality films with high critical temperatures (Tc) [1]. Especially in transition from single- to multi-pixel devices, the properties have to be uniform over a large surface area. On the other hand, novel concepts of second generation quantum devices such as charge quantum interference devices based on coherent quantum phase slip require disordered superconductors with high kinetic inductance [2,3]. NbN is a promising candidate as the Tc (bulk T_C=16\ K) in comparison to TiN, TaN, MoSi or WSi allows for higher operating temperatures, higher switching currents, and thus a better signal-to-noise ratio. Nevertheless, the variety of applications demands for a flexible and adaptable manufacturing process with very good control of the thin-film properties, ideally over a larger surface area.

In this context, plasma-enhanced atomic layer deposition (PE-ALD) exhibits very good thickness homogeneity over a broad surface area as well as a nearly perfect thickness control. But when it comes to quantum applications, homogeneity is not only determined by roughness and layer thickness. Also, electrical properties such as normal sheet resistance, critical temperature, or critical current density must be considered. Up to now, PE-ALD processed NbN achieved Tc of 14 K for a 21 nm thick film [4] and even films with 2.7 nm thickness are still superconductive [2]. NbN films made by PE-ALD revealed a complex chemical composition not only consisting of stoichiometric NbN but also of niobium carbide, niobium oxide, and niobium-oxynitride. We observed that the electrical properties changed drastically, whereas film thickness and roughness remained almost constant. The deviations might originate from the reactor geometry or fluctuations of precursor supply during the deposition process. We will present optimized fabrication recipes for SNSPDs with high Tc as well as for circuits of highly disordered superconducting materials [2,3,5].

References

1. Knehr et al., JVST A: Vacuum, Surfaces, and Films 39 (2021).

2.Shaikhaidarov et al., Nature 608, 45 (2022).

3. De Graaf et al., Nature Phys 14, 590 (2018).

4. Ziegler et al., IEEE Trans. Appl. Supercond. 27, 1 (2017).

5.Mutsenik et al., Low Temperature Physics 49, 92 (2023).

This work was supported by European Union's Horizon2020 under Grant Agreement No. 862660/QUANTUM E-LEAPS as well as by the DFG within the project QSolid (No. 13N16152).

Author Index

Bold page numbers indicate presenter

— F —
Fang, H.: AF3-WeA-12, 1
— I —
Il'Ichev, E.: AF3-WeA-13, 1
— K —
Knehr, E.: AF3-WeA-13, 1
— L —
Linzen, S.: AF3-WeA-13, 1
Liu, B.: AF3-WeA-11, **1**
Liu, Z.: AF3-WeA-12, **1**
— M —
Mutsenik, E.: AF3-WeA-13, 1
— O —
Oeslner, G.: AF3-WeA-13, 1
— R —
Ren, J.: AF3-WeA-12, 1
— S —
Sang, L.: AF3-WeA-12, 1
Stolz, R.: AF3-WeA-13, 1
— Z —
Ziegler, M.: AF3-WeA-13, **1**