Semiconductor News

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From the Editor's Desk

Silicon (Si) has been extensively studied and long being used in semiconductor technology and devices. But in today's scenario, Si based devices face limitations for their application in high power devices due to low value of critical electric field. Recently, gallium oxide (Ga_2O_3) has emerged as a key material for power devices due to its wide bandgap (~5.0 eV) and large breakdown field (8 MV/cm). The critical field of Ga_2O_3 is about twenty times more than Si and twice that of silicon carbide (SiC) and gallium nitride (GaN). This allows Ga_2O_3 to be more capable than existing technologies. These unique properties of Ga_2O_3 offer to operate well in high power electronics and to fabricate solar blind UV photodetectors, solar cells and sensors.

High quality single crystal Ga_2O_3 wafers up to four inch in size are available commercially and are quite inexpensive in comparison to bulk GaN wafers. In the past couple of years, a number of research groups from Japan, Germany, USA, Taiwan and India have initiated research activities in various aspects of Ga_2O_3 material and devices. The growth of high quality Ga_2O_3 thin films is carried out using various techniques such as metal organic chemical vapour deposition (MOCVD), molecular beam epitaxy (MBE), pulsed laser deposition (PLD) and hydride vapour phase epitaxy (HVPE). The devices being explored are Schottky barrier diodes, MESFETs, MOSFETs and MSM UV photodetectors. This material holds lot of promise in future for high efficiency power devices and solar blind photodetectors.

In this issue, a short article written by B. R. Tak and R. Singh from IIT Delhi discusses the important properties of Ga_2O_3 from device perspective. We further invite articles from the members to contribute their scientific research and related activities to this newsletter.

–Uday Dadwal, IIT Delhi

Executive Committee of SSI

Prospects of Gallium Oxide based Materials and Devices

Ga_2O_3 has recently become a prominent and interesting material amongst all distinguished semiconducting oxides such as ZnO, SnO_2 and TiO_2 due to its applications in power electronics, transparent conducting oxide (TCO) electrodes, solar cells, and deep UV devices. Its history started in 1952, when Roy *et al.* reported five polymorphisms of Ga_2O_3 denoted as α-, β-, γ-, δ- and ε-. These phases depend upon various growth parameters and conditions. Among all the existing phases, β-Ga_2O_3 has drawn eminent attention due to its thermal and chemical stability. Remaining phases get converted into β-phase above temperature of 600 °C. In 1960, crystal structure of β-Ga_2O_3 (monoclinic) was investigated by S. Geller (Figure 1) [1]. After the early research in initial dedcades, this material was not paid much attention. In 2012, Masataka Higashiwaki reported about the fabrication of first MESFET based on β-Ga_2O_3 crystal [2]. After that the research on this material has been accelerated due to availability of good quality bulk single crystals and thin films as well as its better material properties than GaN and SiC.

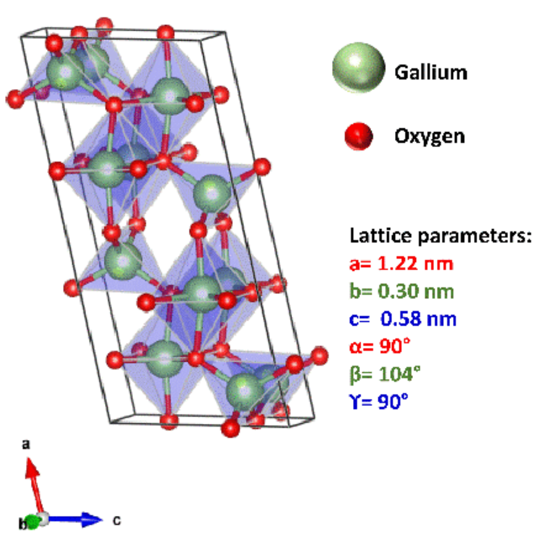

Figure 1: Schematic of the unit cell of β-Ga_2O_3.

Ga_2O_3 has large optical bandgap of 4.5-5.1 eV in the solar blind region. β-Ga_2O_3 has intrinsically *n*-type semiconductor behavior. A few reports have shown that oxygen vacancies are responsible for the *n*-type conduction. Other reports have suggested that oxygen vacancies are deep donors and cannot provide *n*-type behavior. Villora *et al.* reported that Si impurity was responsible for the *n*-type conductivity in Ga_2O_3. Origin of the *n*-type behavior in Ga_2O_3 is still a matter of debate. β-Ga_2O_3 contains various defect states due to its wide bandgap nature. Hence, it exhibits wide range of defect emissions from infrared to UV via these defect states. Table 1 shows the comparison of basic materials properties of β-Ga_2O_3. The major advantage of β-Ga_2O_3 is its Baliga's figure of merit which is much higher than SiC and GaN. Poor thermal conductivity is one of the disadvantages of Ga_2O_3 for power device applications.

Property	**Si**	**4H-SiC**	**GaN**	**β-Ga_2O_3**
Bandgap (eV)	1.1	3.3	3.4	4.7-4.9
Electron mobility ($cm^2V^{-1}s^{-1}$)	1400	1000	1200	300
Breakdown field (MV cm^{-1})	0.3	2.5	3.3	8
Baliga's FOM ($\varepsilon\mu E_b^3$)	1	340	870	3444
Thermal conductivity ($Wcm^{-1}K^{-1}$)	1.5	2.7	2.1	0.23 [010] 0.13 [100]

Table 1: Basic material properties of β-Ga_2O_3.

Corundum structured α-Ga_2O_3 is another interesting phase due to same crystal structure as sapphire which can be used to deposit high quality material. It has optical bandgap of 5.1-5.3 eV. β-Ga_2O_3 can be converted into α-phase at 1000 °C and pressure 4.4 GPa. During the last ten years or so, a numbers of growth techniques have been employed in order to synthesize bulk β-Ga_2O_3 single crystal and thin films. Bulk single crystals of β-Ga_2O_3 can be grown using Czochralski method (CZ), floating-zone (FZ), edge-defined film fed (EFG) or Bridgman growth methods. EFG has been proven to grow single crystal of six inch diameter successfully [3]. Epitaxial and polycrystalline β-Ga_2O_3 thin films have also been deposited using all common techniques such as MBE, PLD, MOCVD, sputtering and ALD. For growth of α-Ga_2O_3, Mist CVD technique is widely used.

International Status

After the first report about MESFET fabrication on single crystal Ga_2O_3 by M. Higashiwaki *et al.*, internationally there has been a steep upsurge of research in the various aspects of Ga_2O_3 materials and devices [4]. Although fabrication of ohmic contacts on Ga_2O_3 is challenging, but reactive ion etching and Si ion implantation have been proven effective methods to make good quality ohmic contacts. MOSFETs with critical field strengths larger than GaN or SiC values have also been demonstrated. There are various research groups active in the area of Ga_2O_3 in Japan, Germany, USA and Taiwan. The main topics of research are bulk crystal growth, epitaxial thin film growth, Schottky diodes and MESFETs for high power electronics, and deep UV photodetectors. There is also an interest on high temperature gas sensors based on Ga_2O_3 thin films and nanostructures.

National Status

At the national level, the first extensive work on Ga_2O_3 was initiated by Prof. R. Singh's group at IIT Delhi around 2011 [5]. They published various articles on Ga_2O_3 nanowires and nanostructures using chemical vapor deposition technique and carried out detailed characterization of the nanomaterials using XRD, Raman, photoluminescence, cathodoluminescence and HRTEM. They also demonstrated the Ga_2O_3 nanowire based UV detectors. After a few years, they started work on the growth of β-Ga_2O_3 epitaxial thin films using PLD technique for the application in solar blind photodetectors. Later on, other groups have also started working on this material. Prof. A. Bhattacharya and Prof. A. Thamizavel's groups at TIFR, Mumbai started the work on single crystal growth of β-Ga_2O_3 using float zone method and also studies on reactive ion etching of Ga_2O_3. Prof. D. Nath's group at IISc Bangalore has initiated work on CVD growth of Ga_2O_3. They have also demonstrated the UV photodetectors on MBE grown β-Ga_2O_3 thin films. Prof. S. Ganapathy's group at Crystal Growth Centre, Anna University, Chennai is doing work on Ga_2O_3 nanostructures for gas sensor applications. Prof. M. Kumar's group at IIT Ropar is working on growth of Ga_2O_3 thin films using sputtering for UV photodetector applications. A couple of other groups in various institutes/universities have also started working on this technologically important material. We hope that in the near future, we will be able to compete at the international level as far as the research on Ga_2O_3 materials and devices are concerned. For that, it is required that intensive and focused work on various aspects of Ga_2O_3 materials and devices is carried out in the future with full support from the funding agencies.

PLD of Ga_2O_3 and deep UV photodetectors

PLD is known as a cost-effective method to grow good quality thin films. Sapphire (*c*-plane) has been used as a foreign substrate due to better lattice matching with Ga_2O_3. The crystalline quality of thin films strongly depends on the growth pressure and temperature. Ga_2O_3 target was ablated using KrF excimer laser to deposit thin films. Low temperature (<500 °C) growth resulted in the amorphous phase whereas crystalline β-Ga_2O_3 phase was achieved at high substrate temperature (800 °C). XRD pattern and AFM topography of the β-Ga_2O_3 film grown at 800 °C is shown in Figure 2 and Figure 3, respectively. Root mean square (RMS) surface roughness of the PLD grown β-Ga_2O_3 thin film wan found to be 2.5 nm. For high performance photodetectors, minimum crystal defects are desired. Hence, intrinsic defects were controlled by oxygen growth pressure.

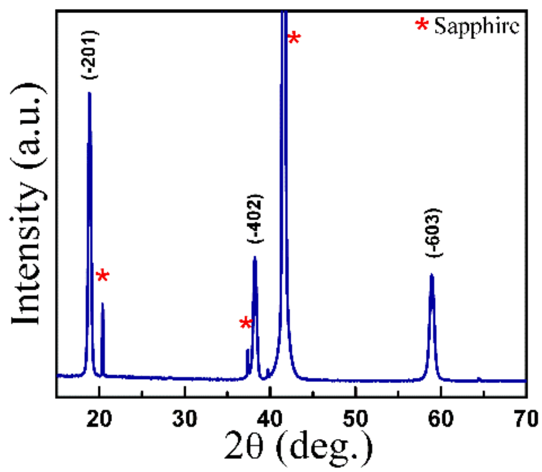

Figure 2: XRD scan of the β-Ga_2O_3 thin film.

Further solar blind UV photodetectors have been designed on β-Ga_2O_3 thin films using optical lithography. Ni/Au bilayer metals were used to fabricate metal-semiconductor-metal (MSM) photodetector devices.

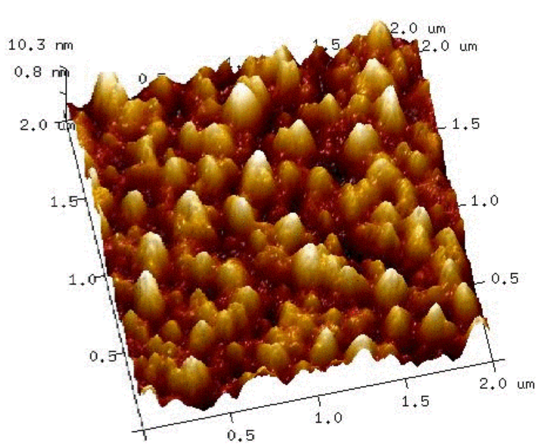

Figure 3: Topography of the β-Ga_2O_3 thin film.

The device structure of the fabricated β-Ga_2O_3 based photodetector is shown in the inset of Figure 4. The dark current of 4×10^{-7} A was obtained at the bias voltage of 15 V. These fabricated devices showed very good sensitivity to 245 nm wavelength signal as depicted in Figure 4.

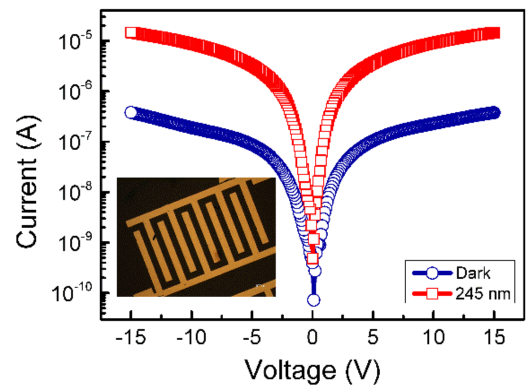

Figure 4: Current-voltage characteristics of the fabricated β-Ga_2O_3 thin film UV photodetector. Inset shows the structure of the fabricated device using optical lithography.

More information about this can be found from the following references:

[1] S. Geller, *Journal of Chemical Physics*, 33, 676 (1960).

[2] M. Higashiwaki et al., *Applied Physics Letters*, 100, 013504 (2012).

[3] http://www.tamura-ss.co.jp/en/products/gao/.

[4] S. J. Pearton et al., *Applied Physics Review*, 5, 011301 (2018).

[5] S. Kumar and R. Singh, *Physica Status Solidi-R*, 7, 781 (2013).

–B. R. Tak and R. Singh, IIT Delhi

Advanced Semiconductor Materials and Devices (ICASMD)

International Conference on "Advanced Semiconductor Materials and Devices (ICASMD)" was recently held in Hyderabad, during 8-10 March, 2018. It was organized by Centre for Materials for Electronics Technology (C-MET), Ministry of Electronics and Information Technology (MeitY), Government of India, in conjunction with its 28th Annual Foundation Day. The venue was Indian Institute of Chemical Technology (IICT) auditorium, Hyderabad. Dr R. Chidambaram, PSA to the government of India was the chief guest of the inaugural function on 8th March, 2018 and Dr. G. Satheesh Reddy, SA to Raksha Mantri graced the occasion as guest of honour. During the inaugural address, Dr. Chidambaram stressed the importance of developing indigenous technology for the sustainable growth of the country. Dr. Satheesh Reddy appreciated the efforts taken by C-MET for the indigenisation of strategic materials such as microwave substrates, Hafnium Sponge, LTCC modules etc. The objective of the conference was to review the requirement driven semiconducting devices based on GaN and SiC as high temperature, high frequency and high power devices and also to bring together scientists, technologists and entrepreneurs actively engaged in the area of advanced semiconductor materials and devices to understand and propagate ideas on technological challenges that need to realize the full potential of these materials for high power electronic devices. The conference was attended by about 200 participants from IITs, universities, research institutes, industries etc. The invited talks were delivered by a number of experts from within India and abroad. Poster session was also held where best poster awards to students were distributed. The concluding session was held in the afternoon of 10th March. The experts gave their views on the further development of semiconductor related activities in India and particularly understanding the specific research challenges related to SiC and GaN based high power electronic device fabrication.

List of invited speakers:

Prof. S. B. Krupanidhi (IISc, Bangalore), Prof. N. B. Singh (University of Maryland, USA), Mr. Deepak Loomba (MD & CEO, De Core Science & Technology Ltd, Noida), Dr. Victor Veliadis, (North Carolina State University, USA), Dr. G. Sanjeev Kumar (PVA CGH, GmbH member of the PVA Tepla AG group Germany), Dr. Govindhan Dhanaraj (Aymont Technology Inc. NY, USA), Dr. B. K. Das (Northcap University, Gurugram, Harayana), Dr. A. K. Garg (Solid State Physics Laboratory, Delhi), Dr. S. T. Ali, Scientist (C-MET Hyderabad), Dr. Seema Vinayak (Solid State Physics Laboratory, Delhi), Prof. Swomitra Mohanty (University of Utah, USA), Prof. Krista Carlson (University of Utah, USA), Prof. M. Ghanashyam Krishna (University of Hyderabad, India), Prof. Rajendra Singh (IIT Delhi, India), Prof. J. Kumar (Crystal Growth Centre, Anna University, Chennai, India), Dr. Ashok V. Joshi (President, Microlin LLC, USA), Smt. V. Sarala (RCI, Hyderabad).

Recent news in semiconductors

1. Structured Materials Industries Inc (SMI) of Piscataway, NJ, USA has carried out studies on the radiation hardness of Ga_2O_3 based power devices. Ga_2O_3 films were grown on bulk doped and undoped Ga_2O_3 and other substrates using MOCVD system. Total ionization dose (TID) and single-event effect (SEE) were used as radiation hardness testing metrics. Potential applications include power devices such as diodes and transistors that may be used in areas like power rectification and RF mixing, among many others. Different combinations of device material properties such as orientation, doping

levels, substrate dopant, and crystal growth technique, including epilayers grown by MOCVD were tested. The fabricated devices include Schottky barrier diodes. The variables were strategically chosen to critically evaluate the potential of Ga_2O_3 based power device performance under different radiation exposures.

2. Researchers in France have recently succeeded in fabricating Ga_2O_3 based metal-oxide-semiconductor field-effect transistors (MOSFETs) on single-crystal (010) Ga_2O_3 substrates. This was done using newly developed technologies for making single-crystal substrates, growing conductivity controlled epitaxial films and fabricating devices. The fabricated MOSFETs showed excellent device characteristics including an off-state breakdown voltage of over 400 V, an extremely low leakage current and a high on/off drain current ratio of more than 10 orders of magnitude. The fabricated devices have also shown good temperature stability with no significant degradation. This research indicates that Ga_2O_3 has more potential than Si and typical wide bandgap semiconductors SiC and GaN for power device applications.