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# Second International Workshop on Zinc Oxide

## October 23-25, 2002
## Holiday Inn I675
## Dayton, Ohio, USA


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### *Purpose and Description*

The format of this workshop will differ from that of the typical conference or symposium by having a very narrow focus, ZnO materials and devices only, and by emphasizing discussion rather than a simple presentation of data. The purposes of the workshop will be to: (1) enhance current ZnO projects by the informal exchange of information; (2) encourage new experimental and theoretical efforts, as needed; (3) discuss the future potential of ZnO, especially now that p-type material has been demonstrated; and (4) provide up-to-date information for any representatives of DoD funding agencies who might be interested in promoting ZnO programs. The workshop will consist of four main sessions: growth, characterization, processing, and applications. More detailed subjects will include (but not be limited to):

- bulk growth
- epitaxial growth
- doping, both n-type and p-type
- structural, electrical, and optical properties
- theory, including band and defect calculations
- processing, including etching, annealing, and formation of ohmic and Schottky contacts
- applications, especially those involving photonic and electronic devices

### *Workshop Schedule*

**Wednesday, October 23**

| | |
|---|---|
| 7:30 am | Registration – Continental Breakfast |
| 8:30 am | Workshop begins |
| 10:15 am | Coffee Break |
| 10:30 am | Workshop continues |
| Noon | Lunch |
| 1:30 pm | Workshop continues |
| 3:15 pm | Coffee Break |
| 5:00 pm | Workshop ends for day |
| | Dinner on own |

**Thursday, October 24**

| | |
|---|---|
| 8:00 am | Continental Breakfast |
| 8:30 am | Workshop re-convenes |
| 10:15 am | Coffee Break |
| 10:30 am | Workshop continues |
| Noon | Lunch |
| 1:30 pm | Workshop continues |
| 5 :00 pm | Workshop ends for day |
| 7:00 pm | Workshop Dinner *(venue to be announced)* |

**Friday, October 25**

| | |
|---|---|
| 8:00 am | Continental Breakfast |
| 8:30 am | Workshop re-convenes |
| 10:15 am | Coffee Break |
| 10:30 am | Workshop re-convenes *(Workshop ends at Noon)* |
| Noon | Workshop Lunch & Networking |

### *Registration Includes*

| | |
|---|---|
| Workshop participation | 3 lunches |
| Abstract book/program | 1 dinner |
| 3 breakfasts | Daily coffee breaks |

*Nonmember registration fee includes complimentary one-year MRS membership*

### *Travel Information*

Dayton International Airport is serviced by all major airlines. Taxis from the airport to the hotel are available at approximately $30 one-way.

The Workshop will be held at the Holiday Inn I675 at 2800 Presidential Drive, Fairborn, OH. Fairborn is a suburb east of Dayton and near Wright State University and Wright-Patterson AFB. For driving information, see **http://walkupright.com/whi/hifairborn/maps.htm**



**www.mrs.org/meetings/workshops/2002/ZnO/**

## MRS Workshop Explored Zinc Oxide Research

The 2nd International Workshop on Zinc Oxide, held as part of the 2002 MRS Workshop Series, was convened in Dayton, Ohio, on October 23–25, 2002. Organized by David C. Look (workshop chair) of Wright State University, Robert F. Davis of North Carolina State University, Cole W. Litton of Wright-Patterson Air Force Base, Yicheng Lu of Rutgers University, Bruno Meyer of University of Giessen (Germany), Chris G. Van de Walle of the Xerox Palo Alto Research Center, and Takafumi Yao of Tohoku University (Japan), the workshop had 52 talks and 42 posters presented from 19 countries. More than 150 scientists from academia, industry, and government laboratories attended the workshop.

There has been great progress in ZnO research since the first International Workshop on Zinc Oxide was held in Dayton in 1999. As one of the most rapidly developing areas in materials, research in ZnO has quickly expanded from photonics and electronics into several emerging areas such as nanostructures and spintronics. The goal of the workshop was to enhance ZnO research by exchanging up-to-date information and assessing the current status and future potential of ZnO. The workshop consisted of sessions on growth, characterization, processing, and device applications.

The session on crystal-growth covered bulk and epitaxial film growth of ZnO and its alloys. GaN, the primary wide-bandgap semiconductor, lacks a lattice-matched substrate for heteroepitaxial growth, and availability of large GaN substrates for homoepitaxial growth. In contrast, ZnO bulk growth technology has been developed by Eagle-Picher Technologies, Cermet, and other companies, to provide commercially available native ZnO substrates. In this workshop, J. Nause (Cermet, Inc.) reported high-quality ZnO bulk crystals grown by a pressurized melt process, which has the advantages of high growth rate and scalability (Figure 1). E.V. Kortounova (Russian Research Institute for the Synthesis of Materials) also reported a ZnO crystal of 45 mm ¥ 45 mm ¥ 20 mm grown by the hydrothermal technique. The resistivity of a 2-in.-diameter ZnO wafer can be controlled from 10 W cm to 1012 W cm. A large size and low cost semi-insulating ZnO substrate technology will be beneficial to high-quality epitaxial growth and device manufacturing.

Growth of hetero- and homoepitaxial ZnO and its (Mg,Cd)xZn1-xO alloy films were reported by various groups using plasma-assisted molecular-beam epitaxy, metalorganic vapor-phase epitaxy, pulsed laser deposition, and rf-magnetron sputtering. For ZnO to become a primary wide-bandgap photonic and electronic material, a controllable bipolar doping technology has to be developed. The workshop presentations indicated that while n-type doping has been well developed with a wide range of doping concentrations up to the transparent conductive oxide level, p-type doping remains a focus of active research. D.B. Eason (Eagle-Picher Technologies) reported a nitrogen-doped p-type ZnO layer grown by molecular-beam epitaxy (MBE) on a semi-insulating ZnO substrate (presented by C.W. Litton), with a hole concentration of 9 ¥ 1016 cm-3 and a hole mobility of 2 cm2/Vs. B.B. Claflin (Wright-Patterson Air Force Base) presented details about the electrical and optical properties of these homoepitaxial MBE p-type ZnO films. The dominant low-temperature photoluminescence peak occurs at 3.318 eV, and shows an excitonlike nature. Significant progress in p-type doping has been made in the last two years; however, much work still needs to be done to achieve controllable, reliable, and device-quality p-type doping, including the development of growth and measurement techniques, as well as theoretical studies.

A. Hoffmann (Technical University of Berlin) discussed the advantages of using nitrogen, which forms as a shallow acceptor in ZnO. Binding energies of approximately 16 meV for the exciton and 165 meV for the nitrogen acceptor were reported. However, secondary-ion mass spectrometry showed a correlation between the concentration of incorporated nitrogen and unintentional hydrogen, an indication of the origin of compensated acceptor states. C.G. Van de Walle provided a theorist's insight on the role of hydrogen in ZnO. Until recently, hydrogen's character as a shallow donor in ZnO was not appreciated. Based on first-principles calculations, Van de Walle described the various configurations that hydrogen can assume in ZnO. Hydrogen strongly interacts with native defects. It activates oxygen vacancies, but it passivates acceptor defects (Figure 2). The calculations show that zinc vacancies may give rise to green luminescence, and that hydrogenation suppresses this luminescence, consistent with experimental observations. First-principles calculations are a powerful tool for understanding the structural and electronic properties of ZnO. For instance, they have also shown that hydrogen acts as an electrically active donor in ZnO, in contrast to hydrogen's behavior in other semiconductors.

There has been significant progress in the development of key ZnO processing technologies, including metallization and etching. The development of Schottky contacts is critical for Schottky diodes and field-effect transistors. Since the first reported Schottky diode on (112-0) ZnO,* Schottky contacts have been successfully developed on c-plane ZnO. In this workshop, B.J. Coppa (North Carolina State University) reported Au Schottky contacts on n-type ZnO. Au was deposited in situ on remote oxygen plasma treated (0001) Zn-ZnO surfaces, resulting in a Schottky barrier height of 0.71 ± 0.05 eV and an ideality factor of 1.17 ± 0.05. The leakage current was ~24 nA at -8.5 V with hard breakdown at -8.75 V. M. Lorenz (University of Leipzig) reported Schottky contacts to c- and a-plane ZnO using Pd and Ag as the contact metal (Figure 3). These Schottky contacts were used successfully for deep-level transient spectroscopy measurements to study defect states in ZnO. For ohmic contacts, including both nonalloyed and alloyed contacts, low, specific contact resistances of ~10-5 W cm2 were reported by several groups. Although the achieved ohmic contact techniques satisfy metal-semiconductor-metal type device requirements, the exact contact mechanisms still need to be fully understood in order to further develop reliable ohmic contacts with lower contact resistances. One of the advantages of ZnO over GaN is that it can be easily etched using wet chemical solutions. In the workshop, K. Ip (University of Florida) presented a dry-etching technique using an inductively coupled plasma (Figure 4). Noncorrosive gases were used to achieve a fast etching rate, with no measurable change in near-surface stoichiometry of bulk ZnO. Further work in the area will aim to develop fully controllable ZnO etching technology, including isotropic and anisotropic etching, etch rate, and selectivity.

ZnO shows great potential for broad device applications, as it is a multifunctional material. The workshop presentations covered recent results in UV photonics, transparent electronics, high-frequency piezoelectric devices, nanoelectronics, and spintronics. M. Kawasaki (Tohoku University) reported ZnO-based thin-film transistors (TFTs). The research goal for this device was to beat the mobility of amorphous silicon TFTs (0.5

cm2/Vs) using a comparable processing temperature (300°C), and to achieve comparable mobility using a maximum processing temperature of 150°C so that polymer substrates could be used. The transparent devices and circuits show promise for replacing amorphous silicon TFTs in liquid-crystal displays (Figure 5). R.D. Vispute (University of Maryland) reported the use of MgxZn1-xO to realize visible-blind (transparent to visible light) ultraviolet photoconductive detectors. The detectors exhibited a high responsitivity of 1200 A/W at a wavelength of 308 nm with 5 V bias, which was comparable with that of its GaN counterpart. Furthermore, Vispute described the fabrication of monolithic multichannel UV detector arrays, and mapping of continuous phase evolution in epitaxial MgxZn1-xO composition spreads. The composition across the chip linearly varied from ZnO to MgO. The resulting continuously changing bandgap was used as a basis for an array of UV photodetectors with a range of detection wavelengths separately activated at different regions on the spread film (Figure 6).

The growing interest in ZnO doped with magnetic impurities for room-temperature spintronics was reflected in the workshop program. D.P. Norton (University of Florida) reported the magnetic properties of Mn-implanted n-type ZnO single crystals codoped with Sn. Ferromagnetism in ZnO, with a Curie temperature of ~250 K, was observed. This exciting research field needs exploratory work in both theory and experiments. According to an estimate from the National Science Foundation (NSF 02-036), the expected market is over $50 billion annually.

ZnO-based nanostructures have become another important emerging research field. K. Thonke (University of Ulm) described a self-organization process for making ZnO nanodots, nano-rings and nanopillars with self-assembling polymers (Figure 7). These nanostructures were produced with sizes of only a few nanometers, far beyond the limits of conventional photolithography processes. S. Fujita (Kyoto University) reported the synthesis of self-organized ZnO nanodots and nanorods by metalorganic chemical vapor deposition. The photoluminescence at 10 K showed a broad shoulder at the higher energy side of free-exciton emission, indicating the quantum size effect, a new and important result for ZnO nanoscale structures.

The workshop was sponsored by the Office of Naval Research, the Air Force Office of Scientific Research, and Wright State University.