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A review of III-nitride research at the Center for Quantum Devices

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ABSTRACT

In this paper, we review the history of the Center for Quantum Devices' (CQD) III-nitride research covering the past 15 years. We review early work developing III-nitride material growth. We then present a review of laser and light-emitting diode (LED) results covering everything from blue lasers to deep UV LEDs emitting at 250 nm. This is followed by a discussion of our UV photodetector research from early photoconductors all the way to current state of the art Geiger-mode UV single photon detectors.

1. Introduction

III-Nitrides, long regarded as a scientific curiosity, have now earned a most respectful place in the science and technology of compound semiconductors and optoelectronic devices. Although the first AlN, GaN, and InN compounds were synthesized as early as 1907 [1], 1910 [2] and 1932 [3], respectively, little significant progress was reported until the end of the 1960s. In the late 1960s and early 1970s the advent of modern epitaxial growth techniques led to a resurgent interest in III-nitrides [4–7]. However, it was not until the 1980s with the advent of the low-temperature GaN buffer [8,9], that material quality became sufficient for device research to begin in earnest. However, little success had been realized in the area of p-type III-nitrides limiting the prospects for junction device. The critical discovery that catapulted III-nitrides to the forefront of modern semiconductor research was Akasaki's demonstration of p-type GaN films through low-energy electron beam irradiation (LEEBI) in 1989 [10] this lead to a swelling of III-nitride research in 1990s.

In 1992 Professor Manijeh Razeghi joined Northwestern University and founded the Center for Quantum Devices (CQDs). The CQD immediately entered the growing III-nitride arena and began a journey that would leave behind a legacy of pioneering research and numerous World's first discoveries covering everything from material development, to light-emitting diodes and laser diodes, to UV photodetectors, focal plane arrays, and avalanche photodiodes. A brief timeline covering the highlights of the CQDs work is shown in Table 1. In this paper, we review the history of the Center for Quantum Devices' III-nitride research.

2. Materials growth

At the beginning of the III-nitride boom of the 1990s there was a great rush to develop device quality material growth. This was a difficult task due to the lack of available GaN substrates, and most growth was conducted on sapphire substrates which lead to very large dislocation densities that made device realization difficult. However, Professor Razeghi had extensive experience in developing growth in the difficult GaInAsP–InP [11], and GaAs and GaInP [12] material systems which aided the CQDs entry into the III-nitride material system.

Early work was conducted in a primitive atmospheric pressure MOCVD reactor. Using that reactor the CQD was among the first groups to realize high-quality AlN on sapphire [13]. However, in January of 1994 through a collaboration between Professor Razeghi and Aixtron the World's first commercial reactor designed for the growth of GaN, the Aixtron 200-4/HT, was designed and installed at Northwestern University [14]. From there the CQD rapidly demonstrated the capability to grow high-quality AlGaN material across the compositional range from AlN to GaN, as shown in Fig. 1 [15].

2.1. Alternative substrates

Throughout the development of III-nitrides there has been a strong desire to find a widely available commercial substrate that is closely lattice matched to GaN and yields optimum growth

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Table 1
Table of the most significant III-nitride accomplishments of the Center for Quantum Devices over the last 15 years.

Year	Accomplishments	References
1993	1st extensive study of choice of substrates for the MOCVD growth of GaN	APL 63, 973 (1993)
1994	1st crystallographic modeling of III-nitride growth	JAP 75, 3964 (1994)
	1st high-quality AlN	APL 64, 339 (1994)
1995	1st high-quality $Al_xGa1_{-x}N$	APL 67, 1745 (1995)
	1st p–n junction GaN photovoltaic detector	APL 67, 2028 (1995)
1996	1st MOCVD growth of GaN on $LiGaO_2$ and $LiAlO_2$	APL 69, 2116 (1996)
1997	1st and only demonstration of entire range of $Al_xGa_{1-x}N$ photoconductors	APL 70, 949 (1997)
1999	1st lateral epitaxial overgrowth of GaN on silicon	APL 74, 570 (1999)
	1st visible blind $Al_xGa_{1-x}N$ photodiodes	APL 74, 1171 (1999)
	1st use of superlattices for enhanced p-type doping in AlGaN	APL 74, 2023 (1999)
2000	1st and shortest wavelength $Al_xGa_{1-x}N$ photodiodes (227 nm)	APL 76, 403 (2000)
2002	1st 280 nm UV LED	APL 81, 801 (2002)
2003	1st 265 nm UV LED	APL 83, 4701 (2003)
2004	1st back-illuminated solar-blind AlGaN photodiode with external QE≥68% at 0 V	APL 84, 1248 (2004)
2005	1st solar-blind AlGaN FPA realized entirely within a University	APL 86, 011117 (2005)
	1st back-illuminated solar-blind AlGaN avalanche photodiodes	APL 87, 241123 (2005)
2007	1st back-illuminated linear mode GaN avalanche photodiodes	APL 90, 141112 (2007)
	1st back-illuminated Geiger mode GaN avalanche photodiodes	APL 91, 041104 (2007)
2008	1st back-illuminated separate absorption and multiplication GaN APD	APL 92, 101120 (2008)
	1st back-illuminated APD with δ-doped p-GaN	APL 93, 211107 (2008)

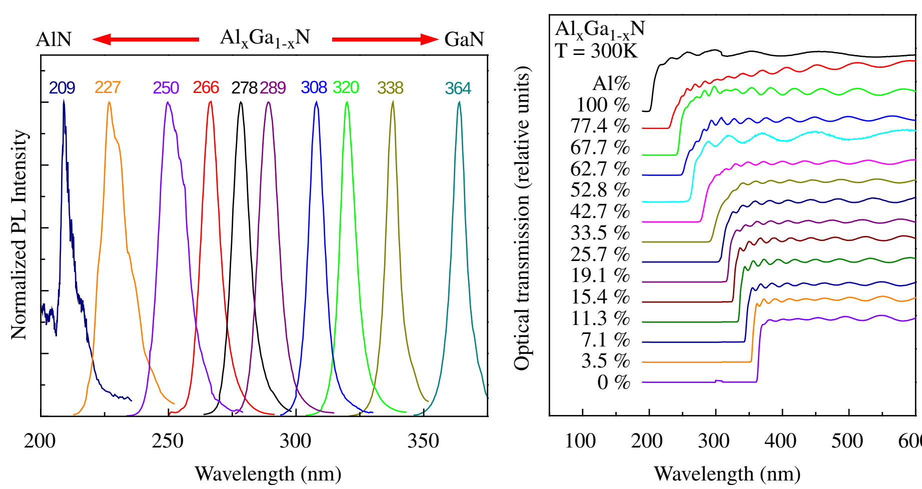

Fig. 1. Optical characterization of AlGaN material grown across the entire compositional range from GaN to AlN: left—photoluminescen and right—optical transmission.

characteristics. The CQD conducted early research investigating different crystallographic orientation of sapphire substrates [16]. They studied growth on various SiC substrates [17]. They also investigated growth on $LiGaO_2$ and $LiAlO_2$ substrates [18].

In addition to pursuing lattice-matched substrates, there is also a desire to push buffer layer technology to even larger lattice mismatches, potentially allowing for the growth of III-nitride on inexpensive silicon substrates. The CQD conducted extensive work on silicon substrates [19], and even developed the first LEO on silicon as discussed below [22].

2.2. III-Nitride crystallography

Despite the poor lattice match to III-nitrides, sapphire is largely the substrate of choice for most research. To better help understand the growth of III-nitrides on sapphire one of the earliest extensive crystallographic models for the crystallography and growth of III-nitrides was developed at the CQD [20]. A key component of this work was the development of a model for the AlN–sapphire interface [21]. This model was latter experimentally verified by conducting high-resolution transmission electron microcopy (HR-TEM) experiments on the AlN buffer to sapphire interface. This HR-TEM (Fig. 2) shows the regular generation of misfit dislocations wherein every nine atoms of sapphire become eight atoms of GaN. Careful control of this interface is critical to the realization of a good compliant AlN buffer and subsequent high-quality material (see Fig. 3).

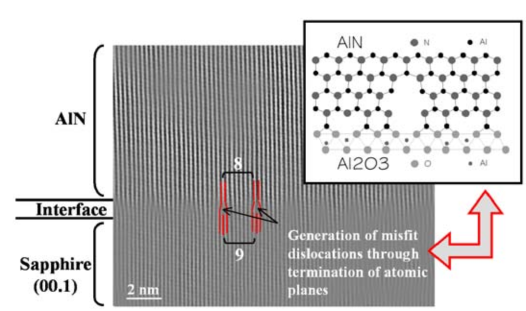

Fig. 2. High-resolution transmission electron microscopy of the AlN buffer–sapphire interface showing misfit generation in accordance with the crystallographic model shown in the inset.