

# InGaN/GaN-based quantum modulators break record for blue electroabsorption

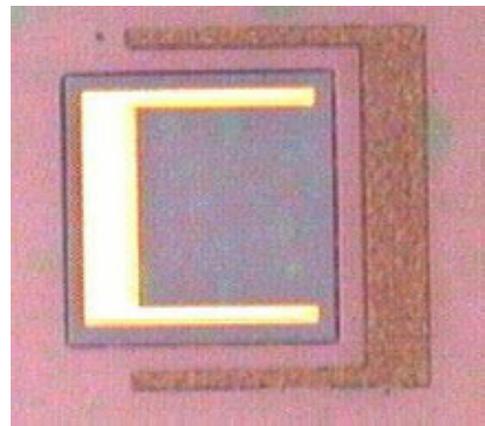
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*Quantum electroabsorption devices operating in the blue range suggest a chip-scale solution for optical clock generation and injection.*

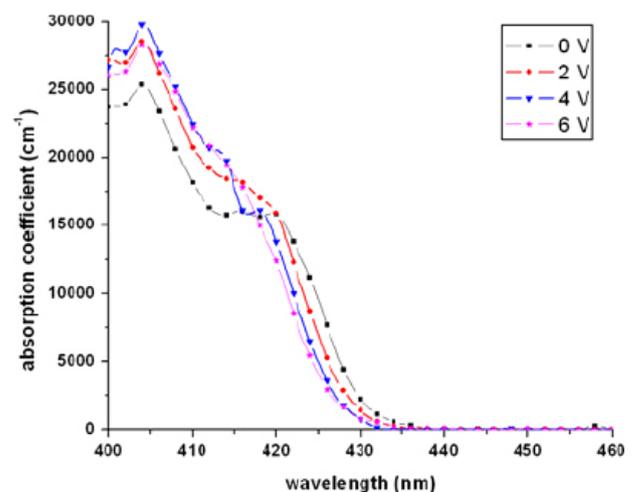
Silicon-based CMOS (Si CMOS) is one of the most mature enabling technologies in wide use today. It has played a major role in advancing the information age by allowing us to perform very complex computational analyses. Over the years, Si CMOS has also evolved to meet expanding need (e.g., as the required speed of operation has increased). Thus, CMOS-based microelectronics have continuously been replaced by their faster successors, and CMOS technology now represents a growing multibillion dollar market.

There is, however, a physical limit to how fast conventional CMOS chips can run. The main constraint is the electrical interconnects. These carry electrical signals, including the data and the clock (which synchronizes digital circuits for proper timing). More specifically, the electrical interconnect lines suffer from their finite resistive-capacitive (RC) time constant, resulting in timing disruptions called jitter and skew. At higher speeds, these discontinuities make up an increasingly significant portion of one clock period. The result is a bottleneck in operating speed that even downscaling interconnects does not solve.

One way to remedy the problem is optical clocking of digital microelectronic circuits. Optical clock injection has been demonstrated at the research level using optical beams commonly in the near infrared (NIR) spectral range. At these wavelengths, necessary chip-scale optoelectronic devices—such as those made of indium phosphate (InP)- and gallium arsenide (GaAs)-based material systems—are readily available. A disadvantage of the NIR, however, is long absorption length, which leads to diffusion tail problems that limit the operation speed of CMOS-based Si photodetectors to  $\sim 1$  Gb/s. Hybrid integration of high-speed GaAs- and InP-based photodetectors onto Si CMOS gets around this limitation but introduces difficulties and drawbacks having

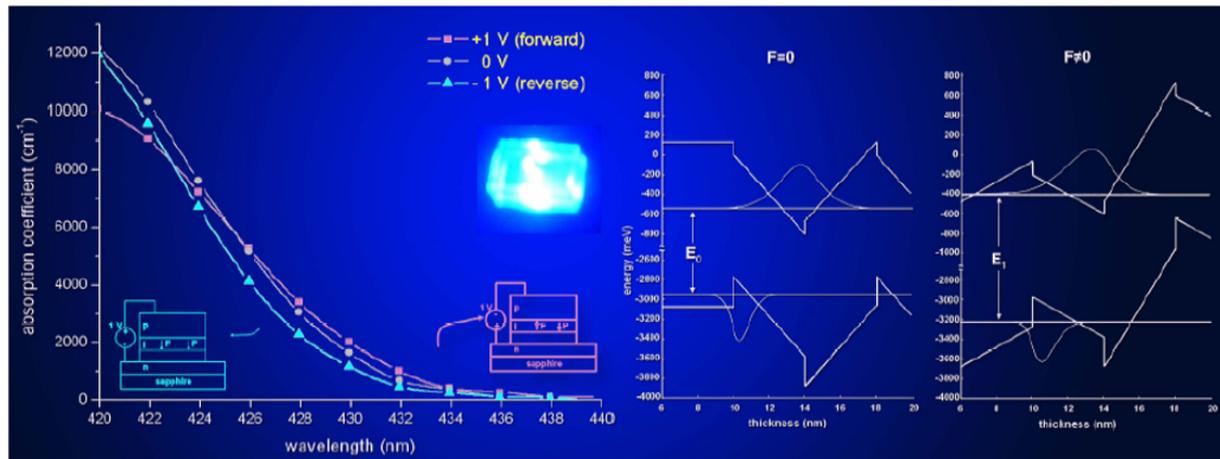


*Figure 1. Top-view micrograph of one of our fabricated indium gallium nitride (InGaN)/GaN-based blue quantum modulators.*



*Figure 2. Optical absorption spectra of our InGaN/GaN-based quantum modulators under different levels of reverse bias at room temperature.*

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**Figure 3.** The electroabsorption of our InGaN/GaN quantum modulators under an electric field applied in different directions (left), the electroluminescence of these devices when forward biased (center), and the energy separation between the first electron and the first hole states under no electric field ( $F=0$ ) and under nonzero field ( $F\neq 0$ ). Here, note that  $E_1 > E_0$ , which implies  $\lambda_1 < \lambda_0$  for the corresponding absorption band edges (right).

to do with post-CMOS fabrication and yield. On the other hand, in the visible wavelength range, the absorption length of Si photodetectors is shorter. Accordingly, Si detectors can be operated much faster, for example, in the blue (400–440nm). Such an implementation scheme is essential for optical clock injection directly into Si CMOS circuits for >10GHz. For that, we proposed and demonstrated indium gallium nitride (InGaN)/GaN-based quantum electroabsorption modulators that operate in the blue range for a possible chip-scale solution to generate and inject optical clocking. We designed and implemented devices that incorporate ~5nm-thick In<sub>0.35</sub>Ga<sub>0.65</sub>N/GaN quantum structures in *pin* diode architecture, as shown in Figure 1.<sup>1</sup>

We grew these quantum structures on the polar *c*-plane of GaN on sapphire in the metal organic chemical vapor deposition system located at the Bilkent University Nanotechnology Research Center. We obtained a zigzag potential profile due to high polarization fields with alternating directions in their epitaxial heterostructures. We studied the electroabsorption behavior of these quantum zigzag structures for proof-of-concept of their use in blue modulation, as depicted in Figure 2. Finally, we experimentally demonstrated an optical absorption change of 6000cm<sup>-1</sup> with the application of a reverse bias of -6V across our diodes (corresponding to 50cm<sup>-1</sup> per 1V/μm field swing) in the blue range (at 424nm) in the highly transmissive region below the band edge.<sup>1</sup>

Instead of the typical redshift of the traditional quantum confined Stark effect (QCSE), we observed in these zigzag structures that the band edge shifted to shorter wavelengths (blueshifts) with the increasing field when applied in the direction opposite to the polarization seen in the wells. We observed a redshift when the applied field was in the direction of well polarization,

as shown in Figure 3. Our quantum analysis of these heterostructures, based on the transfer matrix method, also revealed that the reverse behavior of the QCSE stems from high alternating polarization fields (see Figure 3). For these reasons—both blueshift and behavior contrary to traditional QCSE in steplike other III-V potential profiles<sup>2</sup>—we named this effect reversed QCSE.<sup>1</sup>

The blue electroabsorption we found is the largest ever reported in this wavelength range. It implies that, in principle, a modulation contrast ratio of >10dB is possible with an optical interaction length of ~100μm and a field swing of 2V/μm. Additionally, because of the low parasitic in-series resistance (100Ω) and low capacitance (<100fF for a 3×100μm lateral device area), blue InGaN/GaN quantum electroabsorption modulators hold promise for >10GHz optical clock generation and injection directly into Si CMOS chips in the blue. Moreover, the electroluminescence (see Figure 3) of these devices makes it possible to consider on-chip integration of the blue light source and the modulator for a compact optical clocking scheme.

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Hilmi Volkan Demir received a BSc degree from Bilkent University in 1998, and MS and PhD degrees from Stanford University in 2000 and 2004, respectively. In September 2004, he joined Bilkent University, where he is currently assistant professor jointly in the Departments of Physics and of Electrical Engineering. He is the associate director of the Nanotechnology Research Center. He has received European Union Marie Curie and Turkish National Academy of Sciences Distinguished Young Scientist Awards.

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