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News & Views

GaN-on-Si laser diode: open up a new era of Si-based optical interconnections

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As Si-based electronics technology approaches its scaling limits, it arises great interest in optical interconnections via Si photonics. However, Si with an indirect band-gap structure can hardly emit light. The lack of an efficient on-chip laser source remains as the major roadblock of Si photonics for decades, which recently has drawn renewed research interest. It is highly desirable to grow III–V semiconductor laser directly on Si for a monolithic integration with Si photonics to take the full advantage of low-cost large-scale fabrication platforms [1–3].

There had been only optically pumped lasing reported for GaN-based laser diodes (LDs) grown on Si [4–6]. Because of the large lattice mismatch between GaN and Si and the huge misfit in the coefficient of thermal expansion (CTE), direct growth of GaN on Si often encounters a very high density (10^9–10^{10} cm^{-2}) of threading dislocations (TDs) and a strong tensile stress, even resulting in micro-crack network [7]. Moreover, the presence of AlGaN optical cladding layers grown on GaN contributes additional tensile stress. All these challenges have impeded the realization of electrically injected III-nitride laser directly grown on Si, because laser operation imposes a stringent requirement on defect density and stress management.

In a paper recently published in *Nature Photonics*, Sun et al. [8] reported the first GaN-based blue–violet laser directly grown on Si, operating under a continuous-wave (CW) current injection at room temperature. This breakthrough will speed up the development of Si-based optoelectronics integration and open up a new era of optical interconnections via silicon photonics. To tackle the lattice mismatch and CTE misfit, a stress engineering buffer composed of a stack of Al-composition step down-graded AlN/$Al_xGa_{1-x}N$ multi-layers was inserted between Si and GaN (Fig. 1a). They intentionally utilized the positive lattice mismatch to build up enough compressive strain in the GaN epitaxial film, in order to effectively compensate the tensile stress induced by the CTE mismatch during the cool-down after growth. Meanwhile, the compressive strain facilitates the TDs to incline and annihilate with each other, especially at the interfaces of adjacent buffer layers, giving a high quality GaN film on Si (Fig. 1a). The TD density ($\sim 5.8 \times 10^8$ cm^{-2}) in the GaN film grown on Si is substantially lower than previous reports, as evidenced by the narrow linewidths ($\sim$260 arcsec) of double crystal X-ray rocking curves for GaN(0002) and GaN($10\bar{1}1$) diffractions, as shown in Fig. 1b.

It is worth pointing out that there is a strong interplay between defect reduction and strain relaxation, because the inclination of TDs cancels out some compressive strain and may facilitate the formation of micro-cracks in the GaN film grown on Si. In previous reports [9], typically a series of high Al-composition AlGaN multiple layers (having a limited lattice mismatch with the underlying AlN layer) were deposited on AlN/Si, but gave little contribution to the TD bending/reduction and compressive strain accumulation. In Ref. [8], Sun's research group deposited $Al_{0.35}Ga_{0.65}N$ as the first layer in contact with AlN on Si. An increased compressive strain within the AlN/$Al_{0.35}Ga_{0.65}N$ structure, induced by the $\sim$1.6 % lattice mismatch, facilitates the TDs bending at a larger angle, as well as their annihilation through dislocation interaction.

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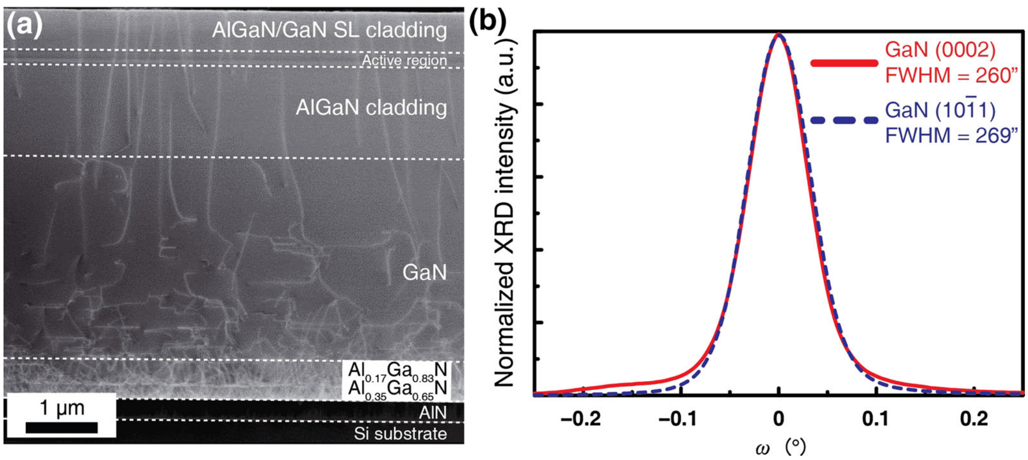

Fig. 1 (Color online) **a** Cross-sectional high-angle annular dark-field scanning TEM image of an InGaN-based laser diode grown on Si. The thickness of the whole epitaxial structure is 5.8 μm. **b** Double crystal X-ray rocking curves for GaN(0002) and GaN(10$\bar{1}$1) diffractions

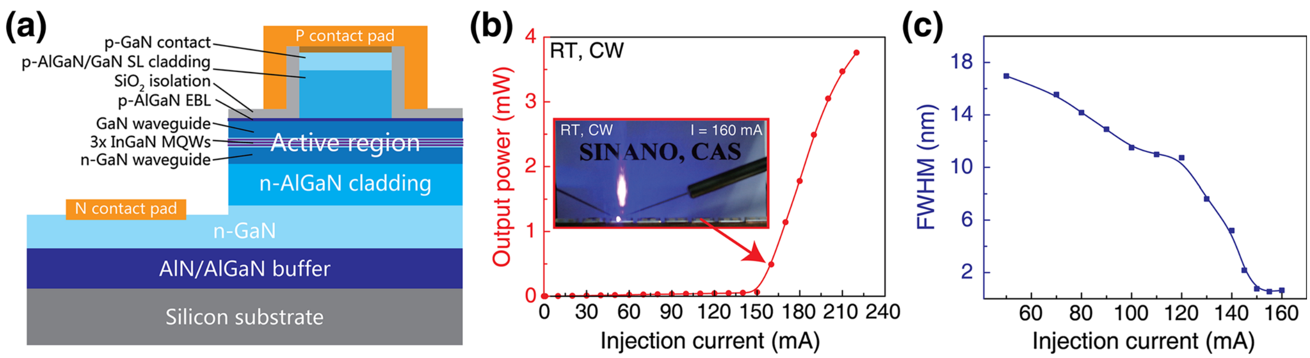

Fig. 2 (Color online) **a** Schematic structure of GaN-based LD grown on Si. **b** *L–I* curve of one as-fabricated GaN-on-Si laser diode measured under continuous-wave current injection at room temperature. The inset: streak line of laser emission at 160 mA (above threshold). **c** FWHM of electroluminescence spectra as a function of the injection current

With a greatly reduced TD density, compressive strain can be built up more effectively during the subsequent growth of $Al_{0.17}Ga_{0.83}N$/GaN. Upon the high quality GaN-on-Si template, InGaN/GaN multiple quantum wells (MQWs) were grown for light emitting diodes (LEDs) [10] and laser diodes (LDs).

The as-fabricated GaN-on-Si LD (Fig. 2a) under an increased CW current injection gave a non-linear up-turn in the light output power, a streak-line far-field pattern of laser emission (Fig. 2b), and a dramatic narrow-down in the full width at half maximum (FWHM) of the electroluminescence spectra (Fig. 2c). These are clear evidence of the stimulated emission lasing at 413 nm with a threshold current density of 4.7 kA/cm^2. The limited lifetime is expected to be elongated to over 10,000 h when the TD density in GaN film is reduced from 10^8 down to 10^6 cm^{-2} through epitaxial lateral overgrowth. With a further improvement in material quality, device performance and lifetime, GaN-on-Si LDs may be commercialized with a cost down by orders of magnitude as compared to the LDs grown on small-size costly GaN free-standing substrates. Moreover, by growing GaN on Si(111)-on-Insulator-Si(100), GaN-on-Si LDs can become a potential on-chip light source for Si photonics.

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Conflict of interest The author declare that he has no conflict of interest.

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