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Fabrication and Characterization of GaN-Based Micro-LEDs on Silicon Substrate *

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GaN-based micro light emitting diodes (micro-LEDs) on silicon (Si) substrates with 40 μm in diameter are developed utilizing standard photolithography and inductively coupled plasma etching techniques. From current-voltage curves, the relatively low turn-on voltage of 2.8 V and low reverse leakage current in the order of 10^{-8} A/cm^2 indicate good electrical characteristics. As the injection current increases, the electroluminescence emission wavelength hardly shifts at around 433 nm, and the relative external quantum efficiency slightly decays, because the impact of quantum-confined Stark effect is not serious in violet-blue micro-LEDs. Since GaN-LEDs are cost effective on large-area Si and suitable for substrate transfer or vertical device structures, the fabricated micro-LEDs on Si should have promising applications in the fields of high-resolution display and optical communication.

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After the first GaN-based blue light emitting diodes (LEDs) were invented,[1] tremendous progress of performance of white LEDs has been achieved by novel device structures[2,3] and improved fabrication methods,[4,5] for applications of solid-state lighting. Compared to standard millimeter-size LEDs, micro-LEDs have pixel spacing of tens of microns, and each pixel can be individually controlled and driven,[6] resulting in ultra-high resolution for display.[7] Compared with the existing OLED technology,[8] micro-LEDs have higher brightness, lower power consumption and better luminous efficiency,[9] leading to a wide range of applications in display and optical communication, etc.[10,11] Nowadays, GaN-based LEDs on sapphire have been widely commercialized. However, sapphire still has some disadvantages, such as low thermal conductivity, large lattice mismatch and significant polarization effect.[12,13] Severe light crosstalk and high thermal mismatch between sapphire and Si-based CMOS backplane will be induced when using LEDs on sapphire for flip-chip micro-displays.[14] Moreover, sapphire substrates need to be detached by the high-cost laser lift-off (LLO) process. In contrast, Si has the advantages of low cost, high electrical and thermal conductivities,[15] which is easy to fabricate low-cost high-efficiency devices and suitable for substrate transfer by the reactive-ion etching (RIE) process.[16,17] In addition, Si can increase color-switching speed of micro-LEDs.[18] Huge cost and mass transfer have always been the two major bottlenecks of micro-LEDs. However, the advantages of Si, micro-LEDs on Si are promising for commercialization with lower cost, easier transfer and faster color-switching speed.[15] To investigate the properties of micro-LEDs on Si, we fabricate GaN-based micro-LED arrays with pixel size of 40 μm in diameter. The obtained devices show good electrical properties with a turn-on voltage of 2.8 V and a reverse leakage current of the order of 10^{-8} A/cm^2. Both the photoluminescence (PL) and electroluminescence (EL) emission peaks are stable at around 433 nm with increasing the laser excitation power and the injection current. At the same time, the relative external quantum efficiency (EQE) of the device is slightly degraded, and the carrier lifetime is increased compared to standard planar LEDs. The effects of quantum-confined Stark effect (QCSE) and efficiency droop are well suppressed compared to micro-LEDs on sapphire.

In our experiment, the GaN-based LED structure was grown on a 2-inch Si (111) substrate by metal-organic chemical vapor deposition (MOCVD). Considering large lattice and thermal mismatches between GaN and Si, a complex buffer layer was employed, which in turn includes an AlN nucleation layer ∼80 nm, a high temperature grown GaN layer ∼400 nm, and an AlN/GaN superlattice layer with

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total thickness ∼60 nm. Above the complex buffer, a 600-nm Si-doped n-type GaN layer, a 5-period InGaN/GaN (2.5 nm/12 nm) multiple quantum well (MQW) and a 150-nm Mg-doped GaN layer were grown. The Mg-doped GaN layer was *in situ* annealed in the reactor with nitrogen ambience at 800℃ for p-type activation.

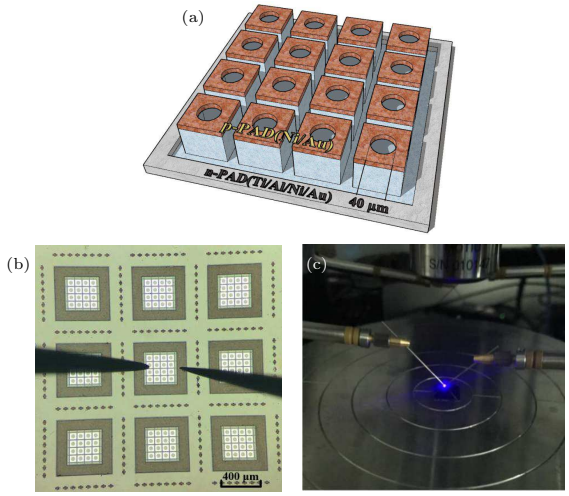

Fig. 1. (a) Schematic diagram of GaN-based micro-LED arrays on Si. (b) Bird's eye view microscope image of GaN-based micro-LED arrays on Si. (c) Micro-LED emission at the injection current of 1 mA.

For device fabrication, as illustrated in Fig. 1(a), a 200-nm SiO_2 mask layer was firstly deposited by plasma enhanced chemical vapor deposition (PECVD). Next, pixel areas were defined through UV optical photolithography with metal nickel (Ni) as mask. The SiO_2 mask layer was chemically etched by the RIE process. Through inductively coupled plasma etching, micro-pillars were etched into the n-type GaN layer with an etch depth of about 450 nm. Then, nitric acid (HNO_3) and buffered oxide etching solution (BOE) were utilized to etch the mask layer. Then, a 200 nm SiO_2 passivation layer was deposited by PECVD. The n-type and p-type metal contact windows were chemically etched by RIE processes, respectively. An n-type electrode Ti/Al/Ni/Au (30/150/50/100 nm) was deposited on the n-pad region and annealed at 750℃ in nitrogen atmosphere for 30 s to form Ohmic contact. Finally, Ni/Au (20/150 nm) was deposited as a p-type electrode and annealed at 570℃ for 5 min in mixed atmosphere (N_2:O_2=4:1). Figure 1(b) illustrates a bird's eye top-view image of the GaN-based micro-LED arrays on Si under the probe station. The p-type electrode was deposited on upper surface of the 4 × 4 micro-pillar arrays surrounded by a common n-type electrode. The GaN-based micro-LEDs on Si with 40 μm in diameter are separated by 5 μm wide deep trench. As illustrated in Fig. 1(c), the emission of the individual micro-LED is bright and uniform under the injection current of 1 mA.

After device fabrication, PL spectra were gathered using a micro-PL system equipped with a 40× objective lens. EL spectra were measured by a UV-visible-infrared spectrometer with optical resolution of 0.1 nm. The reflectivity and angle resolved PL spectra measurements were conducted by the FAR and Rad modes of an IdeaOptics angle resolved microscope (ARM), respectively. The time-resolved photoluminescence (TRPL) spectra were excited by a PDL800 375 nm picosecond pulsed laser and gathered by the PicoQuant single-photon sensitive detector (TCSPC) system.

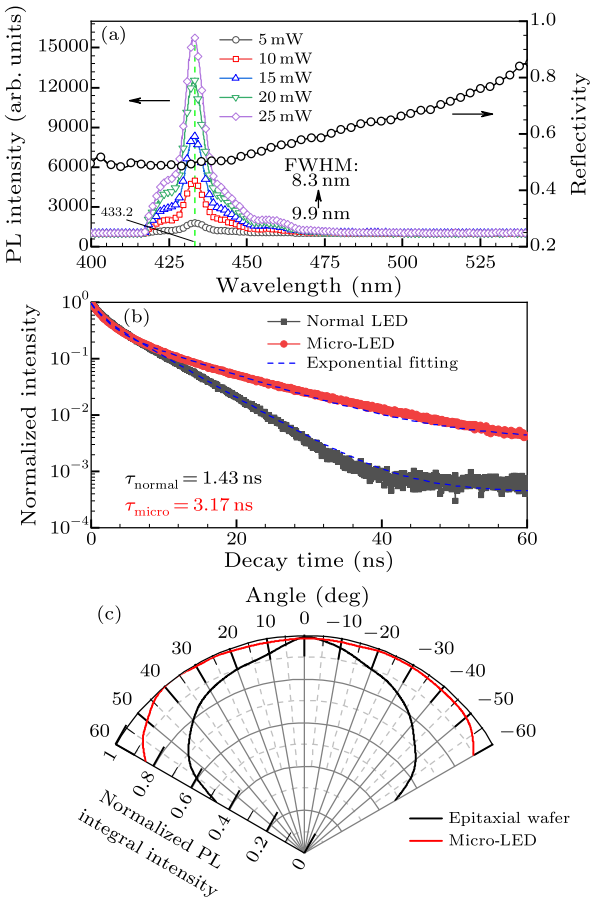

Fig. 2. (a) The PL spectra of an individual pixel in the GaN-based micro-LEDs on Si at the excitation power ranging from 5 mW to 25 mW and the reflectivity spectra of the epitaxial wafer. (b) Normalized TRPL spectra of GaN-based normal LEDs and micro-LEDs on Si. (c) Normalized angular distribution of PL integral intensity.

Room temperature PL spectra of an individual pixel and reflectivity spectra of the epitaxial wafer were first gathered. As shown in Fig. 2(a), the PL emission peak stabilizes at 433.2 nm as the excitation power increases, which is consistent with the epitaxial wafer of 434.2 nm. The full width at half maximum (FWHM) decreases from 9.9 nm to 8.3 nm, which is slightly better than the epitaxial wafer of 11.8 nm to 9.3 nm, indicating superior and stable optical properties. The epitaxial wafer exhibits lower reflectivity near the emission peak because Si has an absorption peak around 400–500 nm, which is helpful for improving the switching contrast of the device.[18] Figure

2(b) illustrates the normalized TRPL spectra of the standard planar LEDs and micro-LEDs. The dotted lines are double-exponentially fitted curves. The carrier lifetime of GaN-based micro-LEDs on Si is 3.17 ns, which is significantly longer than that of standard planar LEDs of 1.43 ns. Due to numerous non-radiative recombination centers in the InGaN/GaN MQWs at room temperature such as defects and lattice dislocations, the non-radiative recombination mechanism dominates during the exciton recombination process. According to the experimental results of TRPL, the carrier lifetime of GaN-based micro-LEDs on Si is longer than that of planar structures, indicating that the non-radiative recombination is suppressed, mainly because the top-down etching removes a considerable amount of non-radiative recombination centers in MQWs. Finally, normalized angular distribution of PL integral intensity ranging from $-60°$ to $60°$ is shown in Fig. 2(c). The normalized PL integral intensity of the micro-LED is always above 0.8 in the range of $-60°$ to $60°$. Compared to the epitaxial wafer, micro-LEDs on Si have a more uniform spatial intensity distribution and a wider emission angle. More light is extracted over a wider range of spatial azimuths, improving light extraction efficiency.

The I–V characteristics and the corresponding leakage current at reverse bias of an individual micro-LED are shown in Fig. 3(a). The turn-on voltage of GaN-based micro-LEDs on Si is estimated to be around 2.8 V, in agreement to the reference.[19] Meanwhile, in the reverse I–V characteristics, the leakage current is 3.4×10^{-10} A at a reverse bias of -4 V. Considering the size of the whole pixel, the reverse leakage current density is of the order of 10^{-8} A/cm^2, which is on the same order of magnitude as micro-LEDs on sapphire[20] and an order of magnitude lower than that of standard planar LEDs.[21] This is due to the optimized material growth and device fabrication process. GaN-based micro-LEDs on Si exhibit excellent electrical properties, which is mainly due to the passivation layer and the effects of dislocation reduction on suppressing leakage.

To further characterize the optical properties of GaN-based micro-LEDs on Si, room temperature EL spectra of an individual micro-LED at the injection current density ranging from 3.3 A/cm^2 to 218 A/cm^2 were measured. As shown in Fig. 3(b), the EL emission peak shifts from 436.1 nm to 433.4 nm as the injection current density increases. Compared to micro-LEDs on sapphire,[22] the offset is negligible within the instrument deviation. The significant polarization effect of sapphire substrate leads to severe QCSE,[15] which limits the improvement of LED luminous efficiency. In contrast, the EL emission peak of micro-LEDs on Si is more stable. Figure 3(c) shows the relationship between EL integral intensity and current density. When the injection current density is below 50 A/cm^2, the integral intensity of EL spectra increases approximately linearly. The integral intensity begins to gradually saturate with the injection current density exceeding 50 A/cm^2. To study efficiency droop behavior of samples, Fig. 3(d) illustrates relative EQE as a function of the injection current density. The relative EQE reaches a maximum at an injection current of 22.2 A/cm^2, and remains 0.7 at 200 A/cm^2. This micro-LEDs mainly work at current density ranging from 10 A/cm^2 to 100 A/cm^2, and the efficiency droop rate is less than 20% for our micro-LED device. Compared to micro-LEDs of similar size,[20,22] the injection current is higher at the maximum EQE point and the relative EQE decays more slowly. The micro size causes strain relaxation and reduced defect density, thus suppressing non-radiative recombination centers. At the same time, the high thermal conductivity of the Si substrate reduces heat accumulation in the device, which relieves the efficiency droop effect and improves the light extraction efficiency.

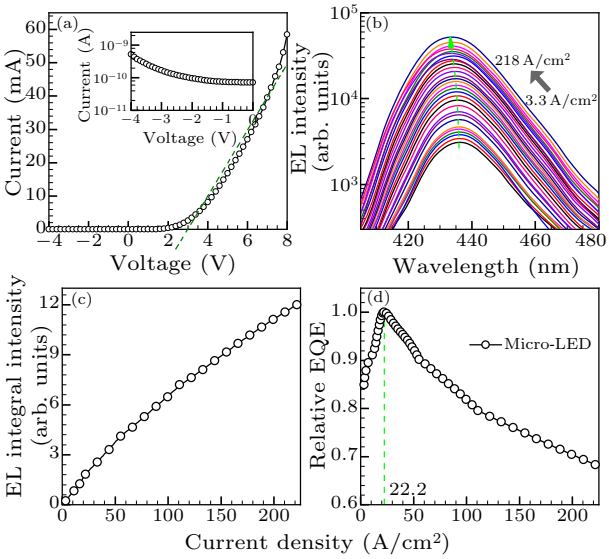

Fig. 3. (a) The current-voltage (I–V) characteristics of an individual pixel in the GaN-based micro-LEDs on Si. The inset is the leakage I–V curve in logarithm scale. (b) The EL spectra of an individual pixel in the GaN-based micro-LEDs on Si at the injection current density ranging from 3.3 A/cm^2 to 218 A/cm^2. (c) EL integral intensity as a function of injection current density. (d) Relative EQE of an individual pixel in the GaN-based micro-LEDs on Si.

In summary, GaN-based micro-LED array devices on Si have been fabricated. Both EL and PL emissions are bright and uniform with peaks at around 433 nm. The non-radiative recombination is suppressed, resulting in significant improvement of the carrier lifetime. Compared with standard millimeter-size LEDs, the fabricated GaN-based micro-LEDs on Si have similar turn-on voltage and lower leakage current, indicating good electrical characteristics. In addition, the relative EQE of the device decays slowly. The introduction of the Si substrate reduces the effects of QCSE and efficiency droop. Si is inexpensive and suitable for substrate transfer, which is advantageous for large-scale applications of GaN-based micro-LED ar-

ray devices in many fields such as display and optical communication.

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