High-Efficiency and Crack-Free InGaN-Based LEDs on a 6-inch Si (111) Substrate With a Composite Buffer Layer Structure and Quaternary Superlattices Electron-Blocking Layers

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Abstract— **In this paper, a composite buffer layer structure (CBLS) with multiple AlGaN layers and grading of Al composition/u-GaN1/(AlN/GaN) superlattices/u-GaN2 and InAlGaN/AlGaN quaternary superlattices electron-blocking layers (QSLs-EBLs) are introduced into the epitaxial growth of InGaN-based light-emitting diodes (LEDs) on 6-inch Si (111) substrates to suppress cracking and improve the crystalline quality and emission efficiency. The effect of CBLS and QSLs-EBL on the crystalline quality and emission efficiency of InGaN-based LEDs on Si substrates was studied in detail. Optical microscopic images revealed the absence of cracks and Ga melt-back etching. The atomic force microscopy images exhibited that the root-mean-square value of the surface morphology was only 0.82 nm. The full widths at half maxima of the (0002) and ($10\bar{1}2$) reflections in the double crystal X-ray rocking curve were ∼330 and 450 arcs, respectively. The total threading dislocation density, revealed by transmission electron microscopy, was $<6 \times 10^8$ cm^{-2}. From the material characterizations, described above, blue and white LEDs emitters were fabricated using the epiwafers of InGaN-based LEDs on 6-inch Si substrates. The blue LEDs emitter that comprised blue LEDs chip and clear lenses had an emission power of 490 mW at 350 mA, a wall-plug efficiency of 45% at 350 mA, and an efficiency droop of 80%. The white LEDs emitter that comprised blue LEDs chip and yellow phosphor had an emission efficiency of ∼110 lm/W at 350 mA and an efficiency droop of 78%. These results imply that the use of a CBLS and QSLs-EBL was found to be very simple and effective in fabricating high-efficiency InGaN-based LEDs on Si for solid-state lighting applications.**

Index Terms— **GaN, composite buffer layer structure, quaternary superlattices EBL, Si substrate, MOCVD, light-emitting diodes (LEDs).**

I. INTRODUCTION

GLOBAL warming and high oil prices have led to much interest in wide band-gap (0.7 to 6.2 eV) InGaN-based semiconductor light light-emitting diodes (LEDs) for their potential to reduce the consumption of limited resources by solid-state lighting (SSL) applications, promoting energy-independence and reducing environmental damage. However, suitable substrates for InGaN-based devices are lacking. Many studies of the growth of InGaN-based epilayers on a variety of substrates, such as sapphire [1]–[4], SiC [5]–[7], free-standing GaN (FS-GaN) [8]–[10], and Si [11]–[19], have been published. Typically, InGaN-based LEDs are grown on sapphire using hetero-epitaxial techniques, such as metal-organic chemical vapor deposition (MOCVD) [20]–[22]. However, its low thermal conductivity and insulating properties make sapphire an imperfect substrate for InGaN-based epilayers. A high price and some mechanical defects reduce the acceptability of SiC as a substrate in the LEDs market. Recently, many works have used FS-GaN as a substrate for the epitaxy of InGaN-based LEDs. Although InGaN-based LEDs on FS-GaN substrate have a high emission efficiency and low droop, FS-GaN is too expensive, preventing end-users from considering the purchase of LEDs devices that are grown on FS-GaN substrate. The cost of InGaN-based LEDs may be the critical factor that determines their use in the SSL field. Among the aforementioned substrate materials, silicon (Si) is regarded as a relatively promising substrate for use in InGaN-based epitaxy because it has two advantages - a low manufacturing cost and the ability to form large size substrate (up to 8-12 inch in diameter). The evolution of

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Si in the semiconductor industry is long: almost defect-free Si substrates can be fabricated, and these Si have many advantages over III-Vs, such as high heat dissipation, strength and difficulty of breaking, and ease of purchase. Additionally Si-based microelectronics can be integrated with InGaN-based optoelectronics. However, growing a device-quality InGaN-based epilayer on a Si substrate is difficult owing to large differences between both their lattice constants and their thermal expansion coefficients. GaN cannot be grown as a buffer layer directly on Si substrates owing to the poor nucleation of GaN on Si [23]. Therefore, many other growth techniques have been used; they include a GaN-free buffer layer [24], [25], a strained layer of AlN/GaN superlattices (SLs) [26], a single AlN buffer layer or multiple layers of AlN/GaN [27]–[29], an AlGaN buffer layer with an Al gradient [30], a patterned Si substrate [31], [32], selective growth [33], [34], a porous Si substrate [35], and Si on an insulator as a compliant substrate [36]. Although the successful growth of crack-free and high-quality GaN epilayer on Si has been reported, the white-light LEDs performance of InGaN-based LEDs on Si remains very poor and no major breakthrough in their emission efficiency or light output power has been made [37]–[41].

In this work, a composite buffer layer structure (CBLS) with multiple AlGaN layers and grading of Al composition/u-GaN1/(AlN/GaN) SLs/u-GaN2 and InAlGaN/AlGaN quaternary superlattices electron-blocking layers (QSLs-EBL) for use in InGaN-based LEDs on Si substrate are designed. The design exploits the concept of compensation for tensile strain and strain engineering. A buffer layer structure and QSLs-EBL that supports InGaN-based LEDs on Si with high emission efficiency are identified by comparing the structural and optical properties of specimens that are fabricated on Si substrates. A white LEDs emitter with an emission efficiency of over 100 lm/W that fabricated from the epi-wafer of InGaN-based LEDs on Si was demonstrated, opening up the possibility of fabricating InGaN-based LEDs on Si for SSL applications.

II. EXPERIMENT

The epitaxial structure of an InGaN-based LED was grown on Si substrate using a commercial low-pressure MOCVD system (Model: Veeco K465i) with a vertical reactor. The liquid/solid MO compounds of trimethylgallium (TMGa), trimethylindium (TMIn), trimethylaluminum (TMAl) and gaseous NH3 were used as the sources of the reactants Ga, In, Al and N, respectively. The carrier gas was a mixture of gaseous N_2 and H_2. The substrates employed herein were 6-inch just (111)-oriented Si substrates. These substrates exhibited n-type conductivity with a carrier concentration of approximately 10^{18} cm^{-3}. Prior to growth, the Si substrate was etched by boiling it in H_2SO_4:H_2O_2 = 3:1 for 15 minutes and then dipped in HF solution (HF:H_2O = 1:10) for 15s to remove the native oxide that formed on the surface of Si substrate. The Si substrate after loading was firstly heated to 1020-1050°C under a H_2 ambient for 5-10 minutes to remove the surface-passivated layer. Following thermal cleaning, the CBLS was grown; it comprised a multiple $Al_xGa_{1-x}N$ layers with an Al step gradient from 1 to 0.17, a 0.5μm-thick u-GaN epilayer (u-GaN1), a sixty-period AlN (1 nm)/GaN (1 nm) SLs, and a 1.5μm-thick u-GaN epilayer (u-GaN2). Here, the multiple $Al_xGa_{1-x}N$ layers comprised a 76nm-thick AlN layer, a 86nm-thick $Al_{0.75}Ga_{0.25}N$ layer, a 133nm-thick $Al_{0.56}Ga_{0.44}N$ layer, a 123nm-thick $Al_{0.43}Ga_{0.57}N$ layer, a 133nm-thick $Al_{0.34}Ga_{0.66}N$ layer, a 143nm-thick $Al_{0.17}Ga_{0.83}N$ layer. Finally, the epitaxial structure of the InGaN-based LEDs was grown on top of the CBLS; it comprised a 3μm-thick n-GaN epilayer, a 30-period $In_{0.07}Ga_{0.93}N$ (2 nm)/GaN (2 nm) pre-strained layer (PSL), a nine-period $In_{0.2}Ga_{0.8}N$ (3.5 nm)/GaN (12 nm) multiple quantum wells (MQWs), a 60nm-thick p-GaN last barrier, an eight-period p-$In_{0.02}Al_{0.23}Ga_{0.75}N$ (2 nm)/p-$Al_{0.1}Ga_{0.9}N$ (2 nm) QSLs-EBL, and a 0.15μm-thick p-GaN epilayer. Fig. 1 presents (a) a photograph of the as-grown epi-wafer of an InGaN-based LED on 6inch Si(111), and a schematic view of the epitaxial structure on (b) Si substrate and (c) sapphire.

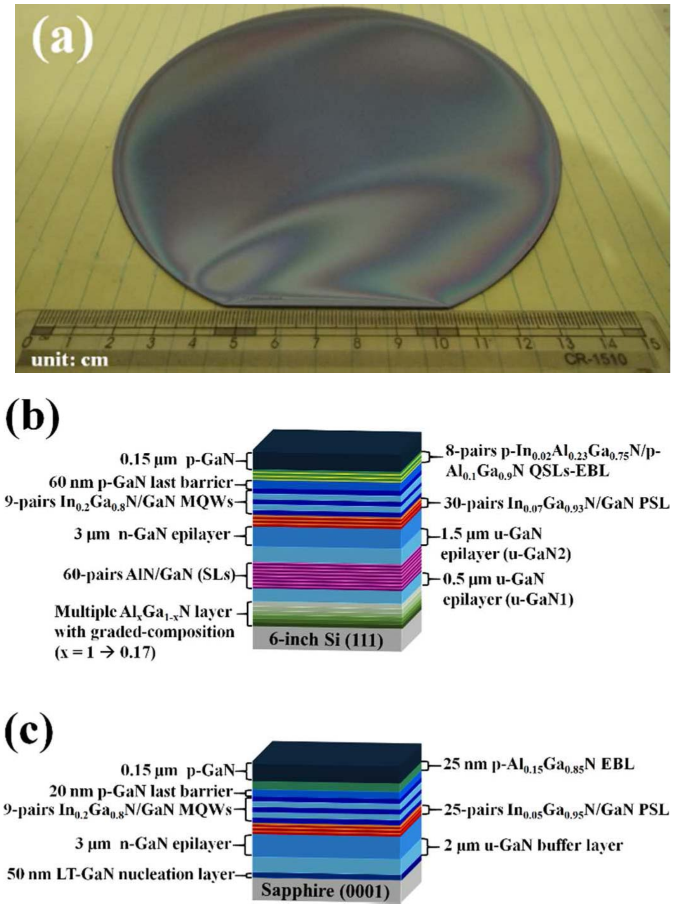

Fig. 1. (a) Photograph of as-grown epi-wafer of InGaN-based LEDs on 6-inch Si (111), and schematic epitaxial structure for InGaN-based LEDs on (b) Si and (c) sapphire.

Following epitaxial growth, the blue InGaN-based LED chip is fabricated. The Si substrate is well known to have a small energy band-gap of approximately 1.12 eV, so it absorbs light with a wavelength of less than 1.1 μm. To eliminate this problem, the Si substrate must be removed. Therefore, a vertical blue LED chip is developed here; its process flowchart is as shown in Fig. 2. The epi-wafer of InGaN-

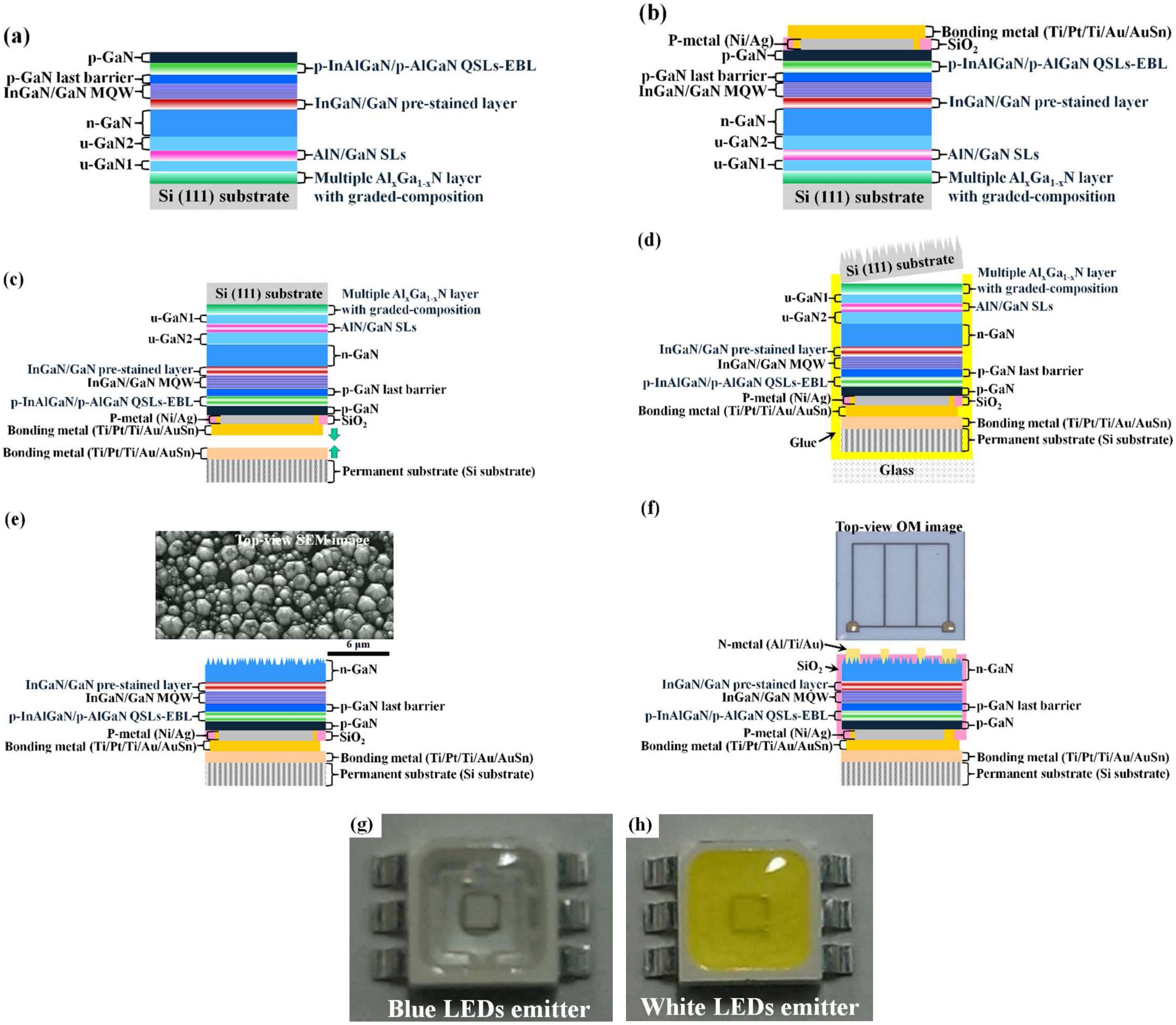

Fig. 2. Process flow for fabrication of blue and white LED emitters (a) epitaxial growth of InGaN-based LEDs on Si substrate by MOCVD, (b) deposition of p-metal layers and bonding metal layers using E-gun evaporator, (c) wafer bonding, (d) removal of Si substrate for epitaxial growth of InGaN-based LEDs by dipping into HNO_3:HF:$NaClO_2$ solution and then CBLS etching by ICP, (e) roughening of n-GaN surface by dipping in KOH, (f) deposition of n-metal layer using E-gun evaporator and then cutting it into squares with dimensions of 1 × 1 mm^2, (g) blue LED emitter that comprised blue LEDs chip and clear lens, (h) white LED emitter that comprised blue LEDs chip and yellow phosphor.

based LEDs on Si was initially degreased in acetone (ACE) and isopropanol (IPA). After cleaning, it was coated with negative photoresist to a thickness of typically approximately 3.6 μm; then a pattern was photolithographically formed with p-metal/bonding metal. Before the metal films were deposited, the specimen was dipped in HCl:H_2O (1:1) for 3 min to remove native oxide from the p-GaN epilayer surface. Then, the multilayered metal system of Ni(10Å)/Ag(3000Å) and Ti(500Å)/Pt(2000Å)/Ti(500Å)/Au(500Å)/AuSn(2μm) that they were fabricated by electron beam evaporation at a pressure of 1×10^{-6} Torr to provide p-metal layers and bonding metal layers, respectively, as presented in Fig. 2(b). Following the deposition of the metals, the specimen was bonded to the permanent substrate (Si) via Ti(500Å)/Pt(2000Å)/Ti(500Å)/Au(500Å)/AuSn(3μm) bonding metal layers, as presented in Fig. 2(c). The Si substrate for use in epitaxy was then removed by dipping it in HNO_3:HF:$NaClO_2$ = 5:1:1 at 80°C for 90 minutes. After the Si substrate for use in epitaxy had been removed, inductively coupled plasma (ICP) is used to etch the CBLS layer, as presented in Fig. 2(d). Additionally, to improve the extraction of light, a 40-50% KOH solution was used to complete the surface roughening of the n-GaN epilayer at 80 °C for three minutes, as presented in Fig. 2(e). Then, the multilayered metal system Al(2000Å)/Ti(500Å)/Au(2.6μm) was deposited on the surface of the roughened n-GaN epilayer to provide the n-metal layers. The blue LED chip was cut into squares with dimensions of 1 × 1 mm^2, as presented in Fig. 2(f).

Finally, the blue LED chip was packaged by a lead frame 5070 (LF-5070) to produce the blue and white LEDs emitters, as presented in Fig. 2(g) and (h), respectively.

In addition, a commercialized vertical LEDs emitter was also fabricated from the epi-wafer of InGaN-based LEDs epitaxial structure on sapphire for comparison. Due to there are many natural difference between sapphire and Si, such as thermal conductivity and lattice-mismatch-induced strain, the optimized growth conditions, layer structure and chip process procedure were different from those used for the InGaN-based LEDs on a Si substrate. In other words, the epitaxial structure of the InGaN-based LEDs on sapphire substrate investigated is depicted in Fig. 1(c), comprising a 50nm-thick low-temperature GaN (LT-GaN) nucleation layer, a 2μm-thick un-doped GaN (u-GaN) buffer layer, a 3μm-thick n-GaN epilayer, a 25-period $In_{0.05}Ga_{0.95}N$ (2 nm)/GaN (2 nm) PSL, a nine-period $In_{0.2}Ga_{0.8}N$ (3.5 nm)/GaN (12 nm) MQWs, a 20nm-thick p-GaN last barrier, an 25nm-thick p-$Al_{0.15}Ga_{0.85}N$ EBL, and a 0.15μm-thick p-GaN epilayer. Following the epitaxial growth, the vertical-type LEDs was fabricated by wafer bonding and laser lift-off (LLO) process, and the detailed chip process procedure was as shown in Ref. [42].

The surface morphology of specimens was observed by atomic force microscopy (AFM) with a scanning area of 10 × 10 μm^2. The crystalline quality and interface of the epitaxial structures herein were evaluated by high-resolution double crystal X-ray diffraction (HRDCXD D8) with Cu Kα radiation as the X-ray source ($\lambda = 1.54056$ Å). The distribution and threading behaviors of dislocations in the epilayer were studied by transmission electron microscopy (TEM). The interfacial microstructures of the epilayer were observed by high-resolution TEM (HRTEM). Finally, the light-current-voltage (L-I-V) characteristics of all packaged LED chips were measured at room temperature in continuous-wave (CW) mode. APSYS software, which was developed by Crosslight Software Inc, was used to determine the physical origin of the improvement in the efficiency of the InGaN-based LEDs on Si. The simulated structures, such as layer thicknesses, doping concentrations, and aluminum composition are the same as the actual devices. The commonly accepted Shockley-Read–Hall recombination lifetime approximately 6 ns, the percentage of screening of 50% and Auger recombination coefficient approximately 10^{-30} cm^6s^{-1} are used in the simulations. Besides, other detailed material parameters used in the simulation are shown in Table I [43].

III. Results and Discussion

Generally, the large difference in thermal expansion coefficients between GaN (5.59×10^{-6} K^{-1}) and Si (2.59×10^{-6} K^{-1}) produces tensile stress in GaN and causes the formation of cracks during the cooling-down from the epitaxial growth temperature. On the other hand, the circular defects can be observed by Optical microscopic if the Ga melt-back etching (Ga-MBE) was formed on the top surface of epi-wafer. Some studies confirmed that the circular defects caused by the reaction of Ga and Si atoms out-diffusing from Si substrate [44]. This phenomenon was reported as Ga-MBE [45]. In the experiment in this work, no any crack was observed and no Ga melt-back etching (Ga-MBE) was identified in this scan, as presented in Fig. 3(a). Fig. 3(b) presents the AFM images of surface morphologies of GaN on Si. As can be seen, a very small root-mean-square (RMS) value of the surface roughness of 0.82 nm was achieved.

TABLE I

Material Parameters Used in the Simulation

Parameter	GaN	InN
m_e/m_0	0.2	0.07
m_h/m_0	1.25	0.6
γ_e	1.0	1.0
$N_{g,e}$ (cm^{-3})	2×10^{17}	8×10^{18}
$\mu_{max,e}$ ($cm^2V^{-1}s^{-1}$)	1000	1100
$\mu_{min,e}$ ($cm^2V^{-1}s^{-1}$)	55	30
γ_h	2.0	2.0
$N_{g,h}$ (cm^{-3})	3×10^{17}	3×10^{17}
$\mu_{max,h}$ ($cm^2V^{-1}s^{-1}$)	170	340
$\mu_{min,h}$ ($cm^2V^{-1}s^{-1}$)	3	3

Fig. 4(a) and (b) plot the (0002) and (10$\bar{1}$2) reflection peaks, respectively, in the HRDCXD rocking curve of the InGaN-based LEDs that were grown on the 6-inch Si substrate. The full width at half maximum (FWHM) of the (0002) peak is only 330 arcsec and that of the (10$\bar{1}$2) peak is only 450 arcsec. The FWHM of the (0002) rocking curve of wurtzite GaN-based films is related to the density of screw or mixed dislocations, while that of the (10$\bar{1}$2) rocking curve is related to all dislocations [46]. The total threading dislocation density (TDDs) can be calculated using the published formula [47]. The calculated total TDDs, including edge, screw and mixed dislocations, is approximately (6-7) × 10^8 cm^{-2}. Although the FWHM of (0002) and (10$\bar{1}$2) reflections of the InGaN-based LEDs on Si substrate does not reach the level of 250-300 arcsec, which was the value obtained from InGaN-based LEDs on sapphire, in the experiment herein, it is lower than has been reported elsewhere, such as the value of 385 arcsec for (0002) and 795 arcsec for (10$\bar{1}$2) that was presented in the work of Jong-Ock Kim et al. [48].

To estimate the crystalline quality of InGaN-based LEDs on Si, TEM is utilized. Two-beam TEM images are captured to determine the nature and density of defects. Heying *et al.* pointed out that pure edge and mixed defects are visible under the g = (10$\bar{1}$0) two-beam condition; pure screw and mixed defects are visible under the g = (0002) two-beam condition [46]. Fig. 5(a) and (d) present bright field scanning TEM images of the InGaN-based LEDs on Si

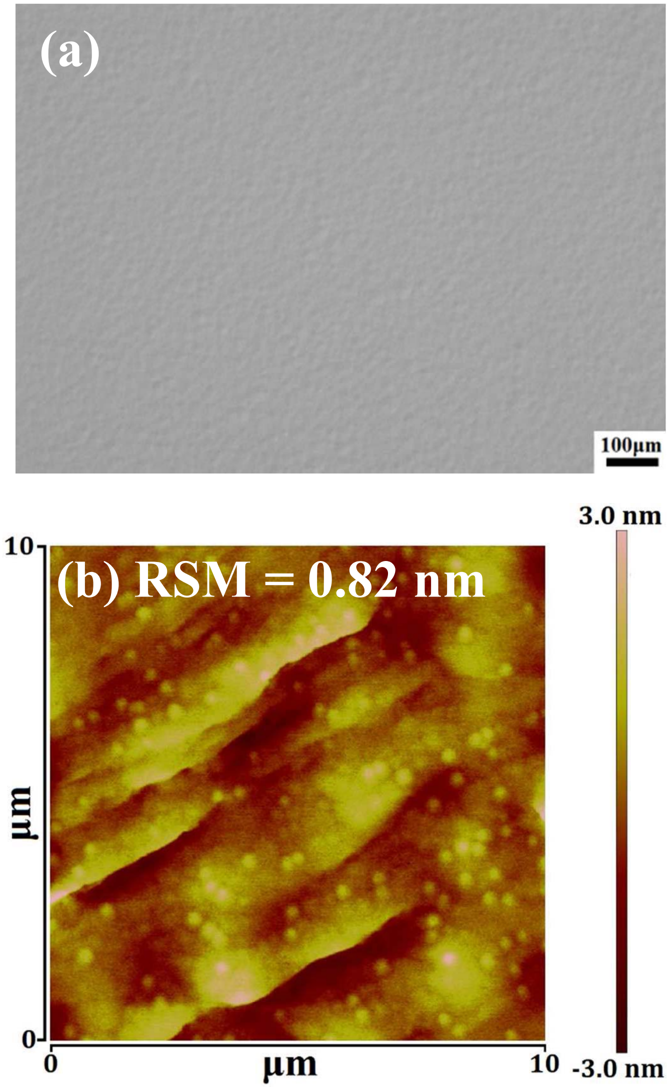

Fig. 3. (a) Optical microscopic and (b) AFM top view of surface morphology of InGaN-based LEDs on Si with CBLS.

herein. Fig. 5(b), (c), (e), and (f) present the two-beam TEM images. No screw-type dislocation is observed in the scanned area. In Fig. 5(a)–(c), many threading dislocations (TDs) are observed at the interface between the multiple AlGaN layers and the Si substrate; their number decreases gradually with the layer number in the multiple AlGaN layers. Therefore, the total TDDs, including edge, screw and mixed dislocations, was estimated to be $\sim 10^{10}$ cm^{-2} at the interface between the multiple AlGaN layers and the Si substrate, falling to $\sim 10^{9}$ cm^{-2} in the u-GaN1 region. When the AlN/GaN SL was introduced, fewer TDs were found in the u-GaN2 region. The densities of the edge, mixed and screw dislocations in the u-GaN2 region were estimated to be 1.5×10^{8}, 4.0×10^{8} and less than 2.6×10^{7} cm^{-2}, respectively. Restated, the total TDD in the u-GaN2 region is further reduced to approximately 6.0×10^{8} cm^{-2}. The n-GaN, MQWs and p-GaN grown on Si substrate with CBLS have many fewer TDs, which radiated vertically from the interface between the multiple AlGaN layers and the Si substrate within the visible range in view. As presented in Fig. 5(d)–(f), the densities of edge, mixed and screw dislocations in the n-GaN region were estimated to be 2.5×10^{8}, 3.6×10^{8} and less than 2.0×10^{7} cm^{-2}, respectively, yielding a total TDD of approximately 6.3×10^{8} cm^{-2}. The densities of edge, mixed and screw dislocations in the p-GaN region were estimated to be less than 4.0×10^{7}, 1.6×10^{8} and less than 2.0×10^{7} cm^{-2}, respectively, yielding a total TDD of approximately 2.2×10^{8} cm^{-2} (Typically: $1 \sim 5 \times 10^{8}$ cm^{-2} for commercialized InGaN-based LEDs grown on Sapphire case). Therefore, quite a large number of TDs can be blocked and bent within the multiple AlGaN layers with the grading of Al composition and AlN/GaN SLs, as presented in Fig. 5(a). The TEM agrees closely with the HRDCXD rocking curve data, further proving that the CBLS is effective in improving the crystalline quality of InGaN-based LEDs on Si substrates. To determine the microstructures in the InGaN/GaN MQW region, HRTEM images, presented in Fig. 5(g), were obtained. Clearly, the MQW region in the InGaN-based LEDs on Si exhibited a more ordered structure, a greater uniformity and a sharper interface between the InGaN well and the GaN barrier.

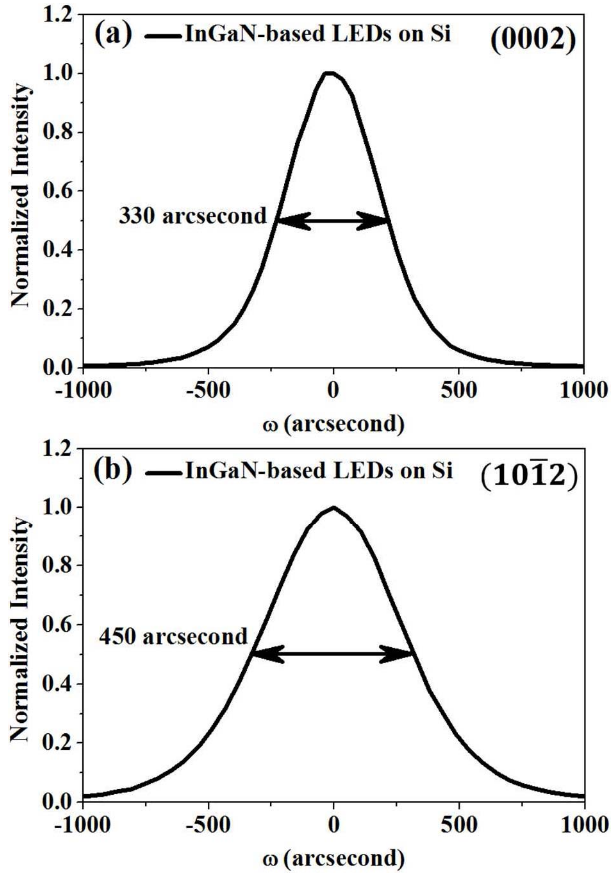

Fig. 4. (a) (0002) and (b) (10$\bar{1}$2) reflections in HRDCXD rocking curves of InGaN-based LEDs grown on Si substrate.

Finally, to understand the performance of devices, the LEDs emitters fabricated on the basis of the material structure of InGaN-based LEDs grown on Si substrates were characterized. In the experiment herein, measurements and of two types of LEDs emitters were made and analyses performed: one was the blue LED emitter that comprised blue LEDs chip and clear lenses; the other was the white LED emitter

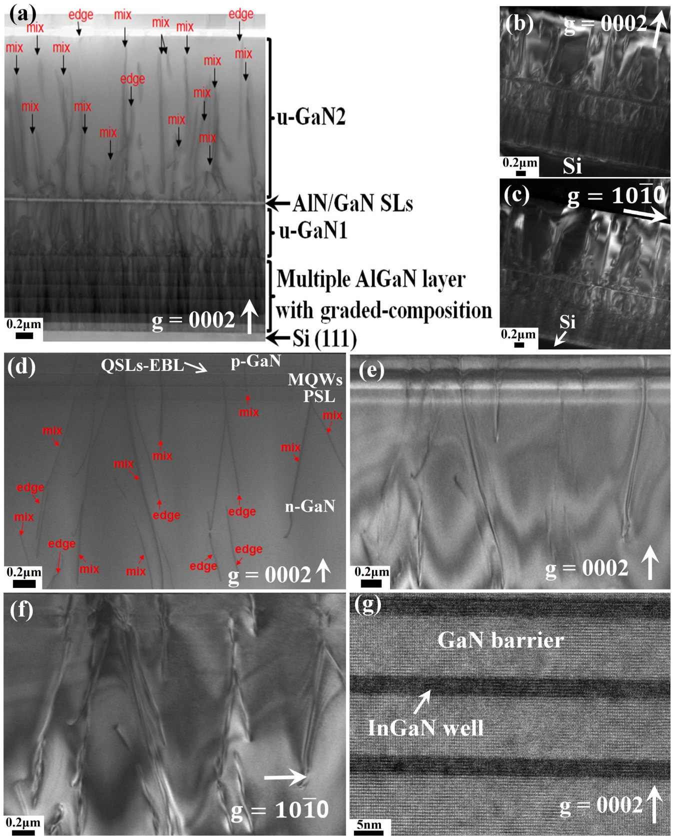

Fig. 5. (a) and (d) Bright field cross-sectional TEM images of InGaN-based LEDs on Si. Two-beam TEM images of InGaN-based LEDs on Si [(b), (c), (e) and (f)]; (b) and (e) dark field cross section, g = 0002; (c) and (f) dark field cross section, g = $10\bar{1}$. (g) The HRTEM image of InGaN-based LEDs on Si.

that comprised blue LEDs chip and yellow phosphor. Most commercialized power chip LEDs are operated at a forward current of 350 mA per 1 × 1 mm^2 of chip area. The Vf, emission power and wall-plug efficiency (WPE, η) of the blue LED emitter, which was fabricated from the epi-wafer of the InGaN-based LEDs on a Si substrate, were approximately 3.1V, 490mW and 45%, respectively, at a forward current of 350mA, as presented in Fig. 6(a) and (b). The strain-induced shift in emission wavelength was approximately 5 nm (from 50 to 700mA), as presented in Fig. 6(b). Additionally, the efficiency droop, defined as $(\eta_{350mA} - \eta_{700mA})/\eta_{350mA}$, was approximately 80%, as presented in Fig. 6(b). From Fig. 7(a), the Vf and emission power of the white LED emitter, which was fabricated from the epi-wafer of InGaN-based LEDs on a Si substrate, were approximately 3.1V and 120 lm, respectively, at a forward current of 350mA, yielding an emission efficiency of as high as 110 lm/W. The efficiency droop was estimated to be approximately 78%, as presented in Fig. 7(b). Therefore, a comparison of the results in Fig. 7 with those in Fig. 6 reveals that the performance of the blue and white LED emitter that was fabricated from the epi-wafer of InGaN-based LEDs on a Si substrate, was comparable to the performance of the blue and white LED emitter that was fabricated from the epi-wafer of InGaN-based LEDs on sapphire because the crystalline quality, stress and recombination rate of electron and hole in the InGaN-based LEDs on the Si substrate was drastically improved by introducing a CBLS and QSLs-EBL. More interestingly, the emission efficiency of the white LED emitter, which was fabricated from the epi-wafer of InGaN-based LEDs on a Si substrate, was successfully increased to 110 lm/W. To the best of the authors' knowledge, this white LEDs emitter with InGaN-based LEDs on a Si substrate is the first to reach an efficiency of 110 lm/W [37]–[41]. We believe that the efficiency of InGaN-based LEDs on Si substrate can be further increased by improving the technique of epitaxial growth and the chip process.

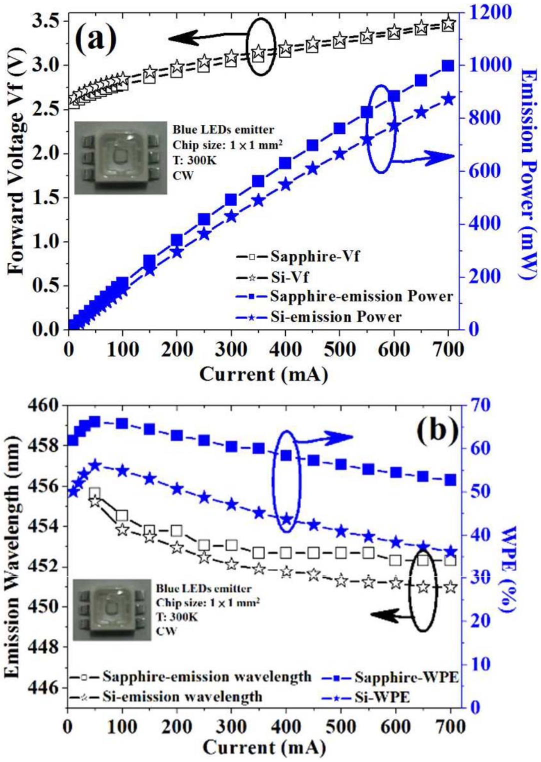

Fig. 6. The electrical characteristic of blue LEDs emitter that comprised blue LEDs chip and clear lens for all the vertical InGaN-based LEDs fabricated. (a) Light-Current-Voltage (L-I-V) curve, (b) Emission wavelength vs injection current and droop behavior.

From the above analyses, the possible mechanisms by which the CBLS and QSLs-EBL yield superior InGaN-based LEDs on Si substrate are as follows.

(a) First, the Al content in multiple AlGaN layers with a graded composition gradually decreased from the Si substrate to the u-GaN1 side, causing the lattice constant of the final AlGaN layer in the multiple AlGaN layers to equal that of u-GaN1, according to Vegard's law [49]. Therefore, the multiple AlGaN layers may generate a graded lattice constant between the upper u-GaN1 layer and the lower Si substrate, yielding a lower TDDs in the u-GaN1 region, as presented in Fig. 8(a).

(b) SLs with strained layers are reportedly effective for reducing the TDDs of epilayer owing to the highly coherent strain energy in the region of the SLs, which arises from the interface misfit strain in the system of SLs. The strain in the region of SLs exerts a net

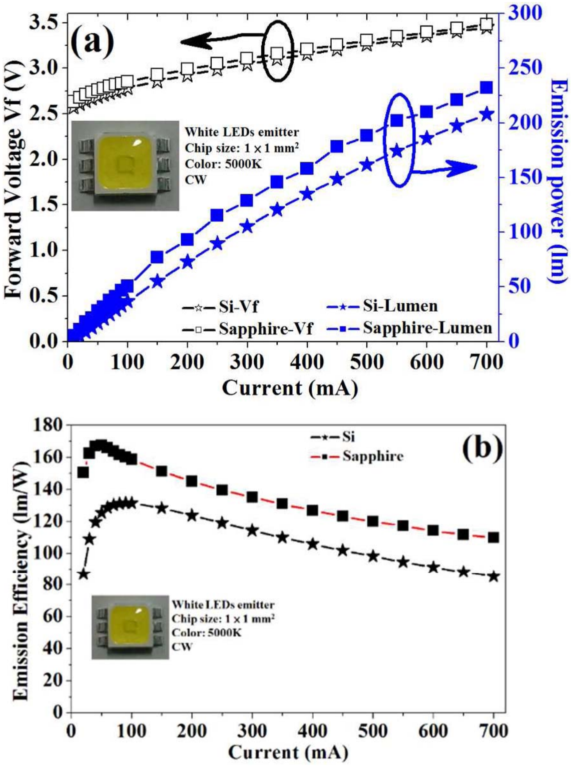

Fig. 7. The electrical characteristic of white LEDs emitter that comprised blue LEDs chip and yellow phosphor for all the vertical InGaN-based LEDs fabricated. (a) Light-Current-Voltage (L-I-V) curve, (b) Droop behavior.

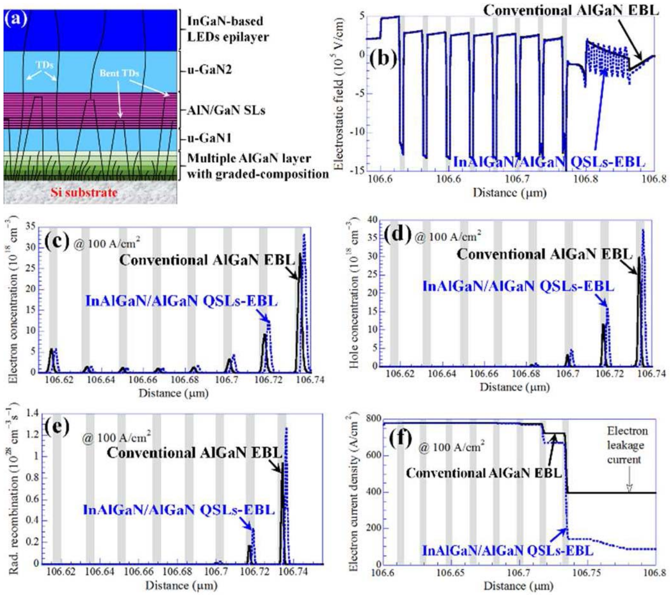

Fig. 8. (a) Potential mechanisms of reduction of TDDs in InGaN-based LEDs on Si with CBLS. Results of APSYS simulation of InGaN-based LEDs on Si with InAlGaN/AlGaN QSLs-EBL under a high forward current density of 100 A/cm2; distribution of (b) electrostatic field, (c) electrons, (d) holes, (e) radiative recombination rate, and (f) electron leakage current.

force on the dislocations causing them to be bent or terminated at the strained epilayer edge without threading through the epilayer to the top surface [50], [51]. In our work, the thickness of each layer in the SL structure is approximately 1 nm. The Peach-Koehler force exceeds the line tension of the TDs, pulling the TDs along the layer interface of the SL structure [52]. The high strain in the SL structure is concluded effectively to bend and suppress the TDs, reducing the TDDs of the epilayer and improving the surface morphology of the specimen, as presented in Figs. 8(a) and 3(b).

(c) To improve the performance of InGaN-based LEDs on Si, an InAlGaN/AlGaN QSLs-EBL is designed to replace the conventional AlGaN EBL. For a general InGaN-based LEDs structure, the interface between the AlGaN EBL and the last GaN barrier is in a strong piezoelectric polarization field [53], which promotes the leakage of carriers. Some research has shown that the lattice constant of InAlGaN with a particular In content almost matches the lattice constant of the GaN epilayer [54]. Some research has also verified that the band-offset between the GaN epilayer and the InAlGaN epilayer is higher than the band-offset between the GaN epilayer and the AlGaN epilayer [55]. Restated, when the InAlGaN/AlGaN QSLs-EBL is used, the higher band-offset and weaker lattice-mismatch-induced piezoelectric polarization field can favor the electron confinement and distribution of holes in the MQW region. The simulation results, as presented in Fig. 8(b)–(f), in this study reveal that the sample with the InAlGaN/AlGaN QSLs-EBL exhibited a weaker electrostatic field than sample with conventional AlGaN EBL, better carrier transport/distribution and lower carrier leakage owing to the weaker polarization effects and improved carrier confinement. A direct consequence is the increase in the radiative recombination rate in the MQW region and, therefore, a rise in light output power.

These improvements that are produced by the use of a CBLS and QSLs-EBL are responsible for the high performance of InGaN-based LEDs on Si with reduced TDDs and strain, and increased light output power and emission efficiency.

IV. CONCLUSION

High performance InGaN-based LEDs on Si substrate were successfully grown without cracking and Ga-MBE, using a CBLS of multiple AlGaN layers with the grading of Al composition/u-GaN1/(AlN/GaN) SLs/u-GaN2 and an InAlGaN/AlGaN QSLs-EBL. The RMS value of surface roughness scanned by AFM was as low as about 0.82 nm. With respect to crystalline quality, the FWHM of the (0002) and $(10\bar{1}2)$ reflection peaks in the HRDCXD rocking curve were approximately 330 and 450 arcsec, respectively. Additionally, cross-sectional TEM observations revealed that the total TDDs, including edge, screw and mixed dislocations, was estimated to be approximately $(3.0 - 6.0) \times 10^8$ cm^{-2}. The results of TEM indicated that the InGaN-based LEDs on the Si substrate were of almost the same material quality as those grown on sapphire substrates (Typically: $1 \sim 5 \times 10^8$ cm^{-2}). Based on the results obtained above, the InGaN-based LEDs on a Si substrate had an emission power of 490 mW at 350 mA in the blue LED emitter and an emission efficiency of 110 lm/W at 350 mA in the white LED emitter. The efficiency droops were estimated to be 80% and 78%, respectively.

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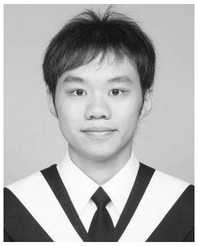

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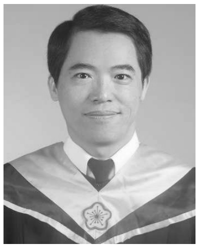

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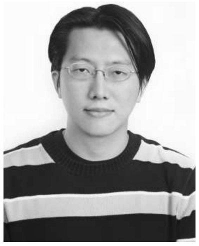

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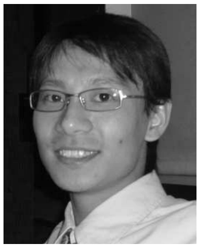

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Dr. Horng received numerous awards recognizing her work on high-brightness LEDs. She has been awarded by the Ministry of Education of Taiwan for Industry/University Corporation Project in 2002, by the National Science Council of Taiwan for the excellent technology transfer of high-power LEDs in 2006, 2008, 2010, and 2011 by Chi Mei Optoelectronics for the first prize of Chi Mei Award in 2008, and by the 2007 IEEE Region 10 Academia-Industry Partnership Award.

Gou-Chung Chi was born in Kaohsiung, Taiwan, in 1946. He received the B.S. degree from National Taiwan Normal University, Taiwan, and the M.S. and Ph.D. degrees in solid-state physics and materials from the Department of Engineering and Applied Science, Yale University, New Haven, CT, USA, in 1970, 1973, and 1976, respectively. From 1977 to 1990, he was a member of the technical staff with AT&T Bell Laboratories. From 1990 to 1994, he was the Director of the Division of Optoelectronics Materials and Devices, Opto-Electronics & Systems Laboratories, Industrial Technology Research Institute, Hsinchu, Taiwan. Since 1994, he had been a Professor and the Director of Optical Sciences Center, National Central University, Zhongli, Taiwan. Since 2009, he has been a Professor with the Department of Photonics, National Chiao Tung University, Hsinchu. His current research interests include wide-bandgap semiconductor and devices (A1GaInP, InGaAsP, and GaN-based materials), and microoptics integrated system. Dr. Chi is a member of the Materials Research Society, Physical Society, Taiwan, and the Electrocins Devices and Materials Association, Taiwan.

Chun-Yen Chang was born in Feng-Shan, Taiwan. He received the B.S. degree in electrical engineering from the National Cheng Kung University (NCKU), Tainan, Taiwan, and the M.S. and Ph.D. degrees from the National Chiao Tung University (NCTU), Hsinchu, Taiwan, in 1960, 1962, and 1969, respectively. He has profoundly contributed to the areas of microelectronics, microwave, and optoelectronics, including the invention of the method of low-pressure MOCVD using triethylgallium to fabricate LED, laser, and microwave devices. He pioneered works on Zn incorporation (1968), nitridation (1984), and fluorine incorporation (1984) in SiO2 for ULSIs, as well as in the charge transfer in semiconductor–oxide–semiconductor system (1968), carrier transport across metal–semiconductor barriers (1970), and the theory of metal–semiconductor contact resistivity (1971). In 1963, he joined the NCTU to serve as an Instructor, establishing a high-vacuum laboratory. In 1964, he and his colleagues established the nation's first and state-of-the-art Semiconductor Research Center, NCTU, with a facility for silicon planar device processing, where they made the nation's first Si planar transistor in 1965 and, subsequently, the first IC and MOSFET in 1966, which strongly forms the foundation of Taiwan's hi-tech development. From 1977 to 1987, he single-handedly established a strong electrical engineering and computer science program at the NCKU, where GaAs, ?-Si, and poly-Si research was established in Taiwan for the first time. He consecutively served as the Dean of Research from 1987 to 1990, the Dean of Engineering from 1990 to 1994, and the Dean of Electrical Engineering and Computer Science from 1994 to 1995. Simultaneously, from 1990 to 1997, he served as the Founding President of the National Nano Device Laboratories, Hsinchu. Since 1998, he has been the President with the Institute of Electronics, NCTU. In 2002, to establish a strong system design capability, he initiated the National program of system on chip, which is based on a strong Taiwanese semiconductor foundry. Dr. Chang is a Member of Academia Sinica in 1996 and a Foreign Associate of the National Academy of Engineering, U.S. in 2000. He was a recipient of the 1987 IEEE Fellow Award, the 2000 Third Millennium Medal, and the 2007 Nikkei Asia Prize for Science category in Japan and regarded as the father of Taiwan semiconductor industries.