GaN Schottky Metal–Semiconductor–Metal UV Photodetectors on Si(111) Grown by Ammonia-MBE

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***Abstract*— For the development of GaN-based ultraviolet (UV) photodetectors, a simple epilayer structure consisting of GaN (600 nm)/AlN (200 nm) was grown on 100-mm Si substrate using ammonia-molecular beam epitaxy growth technique. The epilayers were crack-free and showed good surface and optical quality. Metal–semiconductor–metal (MSM) interdigitated Schottky-based contacts, fabricated using Ni/Au metallic layers, showed a low dark current of 0.43 nA at 15 V. The analysis of dark current as a function of applied bias revealed that the major current conduction mechanism was through thermionic emission over a Schottky barrier of 0.902 eV. Moreover, the Schottky barrier was found to reduce with the bias, which has been attributed to the image force reduction in the devices. The MSM devices exhibited a peak responsivity of 0.183 A/W at an incident wavelength of 362 nm with a UV/visible rejection ratio of 170. The peak responsivity corresponds to external quantum efficiency of ∼70%. The devices also showed good linearity and almost flat responsivity with input power for the applied bias beyond 7 V.**

***Index Terms*— GaN UV detector, MSM, GaN on Si, ammonia-MBE.**

I. Introduction

The increased demand for ultraviolet (UV) photodetectors from civil, industrial, military and space sectors necessitates their development with improved performance at cheaper cost. GaN is one of the key material systems for the development of UV photodetectors because of its wide bang gap, high electron saturation velocity and high breakdown field strength that allow high temperature, high frequency and high power operations [1]. Moreover, the high chemical and radiative hardness of GaN permits the operation of these devices in challenging environments [2]. GaN-based devices on silicon substrates have unique advantages such as availability of large wafer sizes, low cost of production and potential integration with existing Si technology. With these advantages, GaN based photodetectors have been fabricated on Si substrate using metal organic chemical vapour deposition (MOCVD) [2]–[5] and molecular beam epitaxy (MBE) [6]–[9] growth techniques. Lower growth temperatures, sharp interfaces and in-situ monitoring capabilities are some of the advantages of using MBE growth technique. Further, ammonia as nitrogen source in the MBE growth process adds distinctive advantages such as wider growth window, reduced leakage, and improved device uniformity [10]. The authors and others have successfully demonstrated and well-studied GaN based high electron mobility transistor (HEMT) heterostructures on 50-mm [11], [12] and 100-mm [13], [14] silicon substrate by ammonia-MBE growth method. However, studies on GaN based photodetector structures grown by ammonia-MBE on silicon substrate are relatively few [6], [8].

Among different types of photodetectors studied, metal-semiconductor-metal (MSM) photodetectors have advantages such as ease of fabrication, large active area, small capacitance and fast response characteristics [15]. However, MSM photodetectors also suffer from high gain [8], [16]. GaN Schottky MSM photodetectors grown by ammonia-MBE on Si (111) substrate [8] showed high responsivity of 4600 A/W even at an applied bias of 1V, indicating high gain in the device. Such high gain decreases the bandwidth of the device operation. In this work, the gain in the GaN Schottky MSM photodetector devices, grown by ammonia-MBE on 100-mm Si (111) was well controlled and achieved a device responsivity of 0.183 A/W at 15 V of applied bias. Moreover, in the early studies of GaN based photodetectors, Monroy et al. [17] have showed linear characteristics of Schottky based GaN photodetectors on sapphire substrate with a flat responsivity as a function of input power. However, to the best of our knowledge, such linear characteristics for Schottky based GaN MSM photodetectors with flat responsivity as a function of input power and applied bias has not been reported for GaN on Si substrate. Thus, the main objective of this work is to demonstrate the applicability of ammonia-MBE growth technique in developing a simple epilayer structure that can

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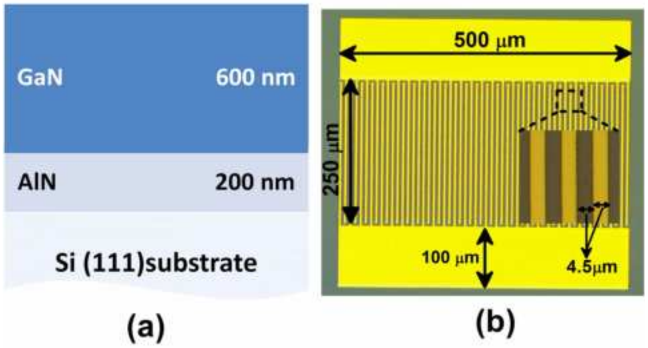

Fig. 1. (a) Epilayer structure of GaN based photodetector on Si substrate. (b) Microscope image of MSM photodetector with the inset showing the zoom-in image of interdigitated contacts.

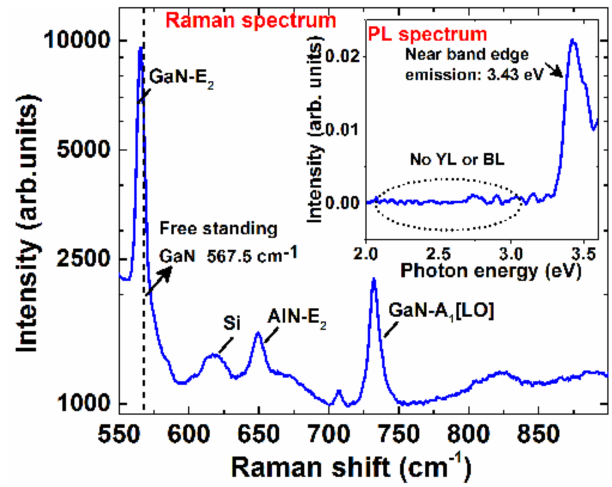

Fig. 2. Raman spectrum of the epilayer structure of photodetector obtained in back scattering geometry. Inset figure shows RT-PL spectrum of GaN epilayer.

produce GaN material on 100-mm Si(111) substrate with a material quality, that is good enough to produce lower leakage currents, higher responsivity, relatively lower gain and flat responsivity characteristics of GaN based MSM PDs.

II. Experimental

The epilayer structure of GaN based photodetector on 100-mm Si (111) grown using ammonia-MBE is shown in Fig. 1 (a). Unlike the epilayer structure for high electron mobility transistors grown using ammonia-MBE on Si substrate, where thick GaN buffer layers and the use of AlN/GaN [11], [18] or AlGaN/AlN/GaN [19] stress mitigating layers (SMLs) are necessary, the epilayer structure for photodetector application in this study was designed using simple AlN and GaN epilayers with thicknesses of 200 and 600 nm, respectively. However, the initial nucleation of AlN by using intentional nitridation first approach was kept same in the growth of this structure also [13], [20]. AlN and GaN epilayers were grown at growth temperatures of 920 and 800 °C, respectively. Their corresponding growth rates were kept at 0.13 and 0.70 μm/hr., respectively. The GaN growth was performed at a high V/III ratio of 950. The complete details about the nucleation and growth of GaN and AlN epilayers on Si by ammonia-MBE can be found elsewhere [13].

Metal-semiconductor-metal (MSM) interdigitated structures were fabricated on GaN with Ni/Au contacts of thicknesses 150/350 nm. Figure 1(b) shows the microscope image of the MSM photodetector with inset figure showing the zoom-in image of the interdigitated electrodes and the corresponding device dimensions. Current-voltage characteristics of the devices in the dark and under illumination were measured using Keithley picoammeter and voltage source in the DC measurement mode. The photodetector spectral responsivity characteristics were studied with amplitude modulation technique. The monochromatic light was generated by a combination of Xenon lamp source and JY-IHR 550 monochromator, and modulated by a mechanical chopper at a frequency of 130 Hz. The photocurrent was collected and detected by a lock-in amplifier (SR 830) [21]. The optical power density of the incident light was varied using a set of neutral filters and calibrated using a UV enhanced Si photodiode.

III. Results and Discussion

The microscopic investigation of the grown epilayers revealed no surface or buried cracks in the epilayer structure. It indicates that GaN layer has sufficient residual compression at the end of the growth, which compensates the tensile stress generated during the cool down resulting in a crack-free wafer. The atomic force microscopy (AFM) investigation of the surface revealed mound type surface morphology [14], which is a characteristic feature of ammonia-MBE growth [22]. The root mean square (RMS) surface roughness measured was $\sim$2 nm for a scan area of 5 $\times$ 5 μm^2. The crystal quality of GaN epilayer was investigated using HR-XRD rocking curve scans along (0002) and $(30\bar{3}2)$ planes of GaN, whose full width at half maxima (FWHM) determined were 900 and 2919 arc-sec, respectively. The FWHM of the rocking curves along GaN(0002) and GaN$(30\bar{3}2)$ represent screw and edge components of dislocation density, with their estimated values from the rocking curve scans of 1.85×10^9 and 5.14×10^{10} cm^{-2}, respectively. The FWHM of rocking curve along GaN(0002) is comparable to that of thick GaN buffer layers grown using AlN/GaN SMLs [14], whereas, the FWHM of rocking curve along GaN$(30\bar{3}2)$ plane is relatively higher. This can be attributed to the lower thickness of GaN and lack of multiple interfaces in this structure, which lead to relatively lesser annihilation of edge type dislocations by dislocation bending and looping mechanism [23]. However, the designed simple epilayer device structure with a thinner GaN layer helps to achieve higher throughput and lower cost.

Raman spectrum obtained on the sample is shown in the Fig. 2. It consists of peaks corresponding to GaN-E_2, GaN-A_1[LO] and AlN-E_2 phonon modes in addition to peaks corresponding to Si. The GaN-E_2 phonon peak positon was observed at 565.5 cm^{-1}, whereas, the free standing GaN-E_2 peak positon was reported as 567.5 cm^{-1} [24]. This shows the tensile nature of the epilayer with a tensile stress of $\sim$ 465 MPa, estimated using the relation between biaxial stress and Raman shift of $\Delta\omega = 4.3$cm^{-1} GPa^{-1} [24].

The inset of Fig. 2 shows the photoluminescence (PL) spectra obtained at room temperature (RT) using He-Cd laser

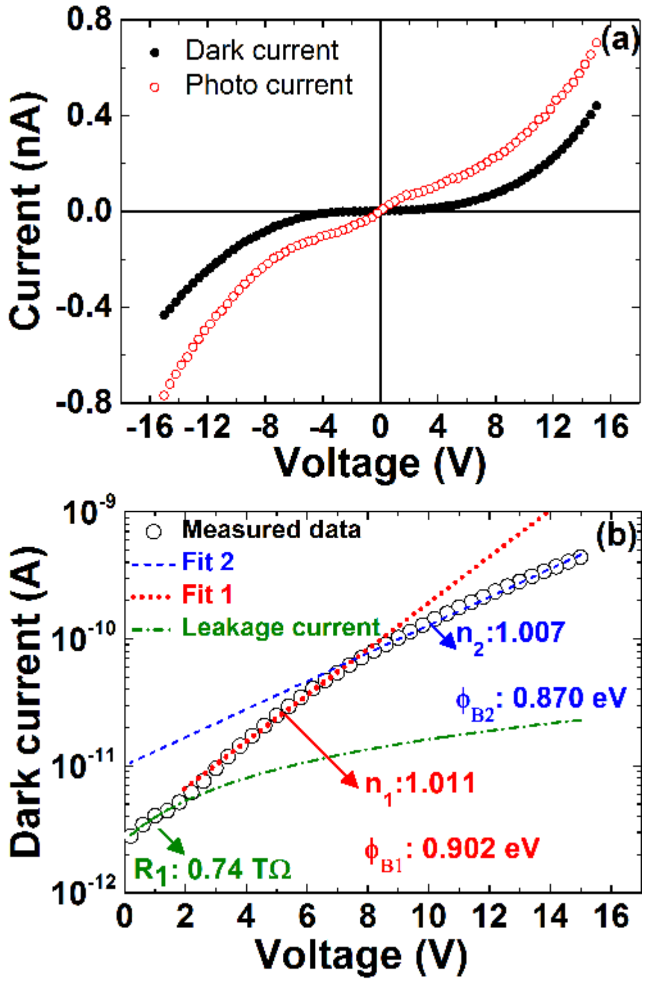

Fig. 3. (a) Dark and photocurrent properties of GaN MSM devices. (b) Semi-log plot of dark current and its corresponding fit with MSM current transport equation.

source with a wavelength of 325 nm. The PL spectrum shows near band-edge luminescence at 3.43 eV with no signal from either yellow luminescence (YL) (∼2.2 eV) or blue luminescence (BL) (∼2.9 eV) [25]. The absence of YL and BL suggests that the corresponding defect states are at minimal level in these samples, indicating good quality of GaN epilayer.

Figure 3a shows the dark and photocurrent measurements of the MSM device at room temperature. As shown in the figure, the device shows a low dark current of 0.43 nA at 15 V and exhibits a good photocurrent response with the illumination of Xenon lamp source. It can be noticed that the photocurrent increases linearly with the applied bias up to 1.8 V, beyond which the current shows a non-linear behaviour. Except for the linear portion, the symmetric non-linear nature is consistent with the characteristic behaviour of MSM devices in the model proposed by Elhadidy et al. [26]. As described in this model, at the studied applied biases, most of the applied voltage is dropped across the reverse biased cathode and hence this junction dominates the IV measurements of MSM devices. Moreover, references [27] and [28] indicate that the dark current in MSM devices is given by the sum of electron and hole currents at cathode and anode, respectively. The hole current at anode for a wide band gap semiconductor materials can be neglected due to high Schottky barrier height for the holes at anode (For symmetric MSM devices, $\phi_{n1}+\phi_{p1} = E_g$, where ϕ_{n1}, ϕ_{p1} are Schottky barrier heights for electrons at cathode, ∼0.9 eV for Ni/GaN interface, and holes at anode, respectively; E_g is the band gap of GaN). Hence, effectively, IV characteristics of an MSM device can be described by the general form of current voltage (I-V) characteristics of a Schottky junction at reverse biased cathode as described by the equation [29]

$$I = I_0 \exp\left(\frac{eV}{nkT}\right)\left[1 - \exp\left(\frac{-eV}{kT}\right)\right] \tag{1}$$

where, $I_0 = AA * T^2 \exp\left(\frac{-e\phi_B}{nkT}\right)$

Here, A, $A*$, T, V, ϕ_B and n are area, Richardson constant, temperature, applied bias, Schottky barrier height and ideality factor, respectively.

It can be noticed from Eq. 1 that for an ideality factor of 1 ($n = 1$), the equation turns into a simple form of ideal Schottky diode equation with the current flow governed only by thermionic emission. However, a deviation in the ideality factor from 1 indicates that the effects such as image force lowering [30], leakage current [31] and tunneling [29] may also affect the current characteristics. Moreover, studies have shown that tunneling current is the dominant mechanism if the ideality factor is beyond 2 ($n > 2$) [29].

Figure 3b shows the semi-log plot of dark current and its corresponding fit with equation 1 for an applied bias exceeding 1.8 V. Up to a bias of 1.8 V, the I-V characteristic illustrates a linear behaviour with a resistance of 0.74 TΩ, which can be attributed to the leakage current in the device [31]. This explains the linear nature of photocurrent in this region. However, when the applied bias is beyond 1.8 V, the fit obtained using Eq. 1 shows majorly two regions with the fit 1 extending from 2 to 7 V and fit 2 from 7 to 15 V. The resultant ideality factor and Schottky barrier height obtained from fit 1 are 1.011 and 0.902 eV, respectively, while they are 1.007 and 0.870 eV, respectively in the case of fit 2. Thus, beyond 1.8 V, the thermionic emission is found to be the major current transport mechanism as the ideality factor is closer to 1. Moreover, the reduction in the average Schottky barrier height from 0.902 to 0.870 eV with the applied bias indicates the presence of image force lowering [30] in the MSM device. The obtained Schottky barrier height is close to the reported Schottky barrier heights of 0.95 to 0.99 eV [32], which suggests that the metal-semiconductor junction is of good quality.

The MSM photodetector responsivity, R ($R = \frac{I_{ph}}{P_{in}}$ where I_{ph} and P_{in} are the photocurrent and power of incident light, respectively) as a function of wavelength of the incident light with a power density of 0.8 W/m^2 and at different applied bias are shown in Fig. 4.

For the incident light with a wavelength of 362 nm, the device showed a peak responsivity of 0.183 A/W for an applied bias of 15 V. This corresponds to an external quantum efficiency ($EQE = R\left(\frac{hc}{\lambda}\right)$ where h, c and λ are Planks constants, velocity of light and wavelength of incident light,

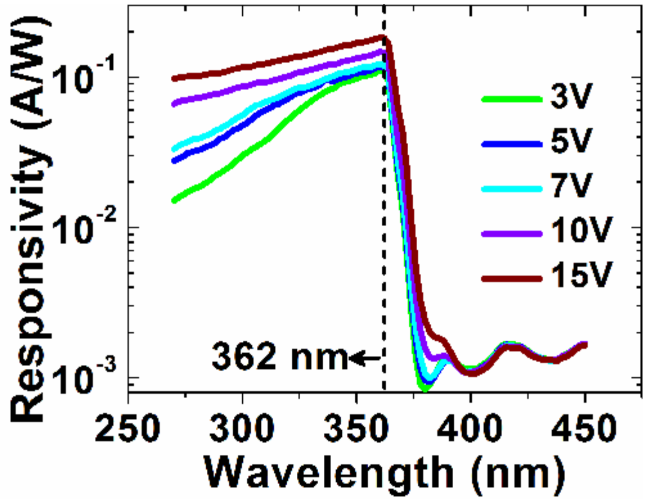

Fig. 4. MSM photodetector responsivity as a function of wavelength of the incident light at different applied biases.

respectively) of ~70%. A sharp cut-off in the responsivity can be observed when the wavelength of the light is beyond 382 nm, indicating good selectivity of response for UV detection with an observed UV/visible rejection ratio $\left(\frac{R_{362nm}}{R_{400nm}}\right)$ of ~170. The observed higher external quantum efficiency in the devices can be attributed to the good material quality of grown GaN as indicated by PL and Raman measurements as well as to the presence of gain in the MSM devices (discussion on the gain is presented in the following paragraphs). However, similar devices grown by ammonia-MBE growth technique with 1 μm GaN epilayer, grown using AlGaN/AlN stress mitigating layers on Si(111) substrate resulted in a very high responsivity of 4600 A/W with a high gain [8]. In comparison, the obtained lower dark current and lower gain in this work can be attributed to the improved material properties due to the intentional nitridation-first approach and the higher V/III ratio growth conditions of ammonia-MBE grown GaN, irrespective of not using any stress mitigating layers and thick GaN epilayer in the current structure.

Figures 5 (a) and (b) show the photocurrent and responsivity, respectively of the MSM photodetector as a function of input power of the incident light at 362 nm. As shown in Fig. 5(a), the photocurrent increases linearly as a function of incident power at all the applied bias. Moreover, it can also be observed from Fig. 5 (a) that the slope of the linearity changes with the applied bias, suggesting variation of the responsivity with the bias. This can be explicitly observed in Fig. 5 (b), where the responsivity shows increment with the increase of applied bias. This behaviour can be attributed to the gain in the devices due to the image force lowering of Schottky barrier height. In addition, the increased charge collection efficiency with increased bias could be another reason.

It can also be observed from Fig. 5 (b) that the responsivity is almost flat as a function of input power of incident light for all applied bias $\geq$ 7 V. However, at a lower applied bias of 5 V, the responsivity increases with the increase in the incident input power up to $\sim$ 0.25 W/m^2, beyond which the responsivity shows almost saturation.

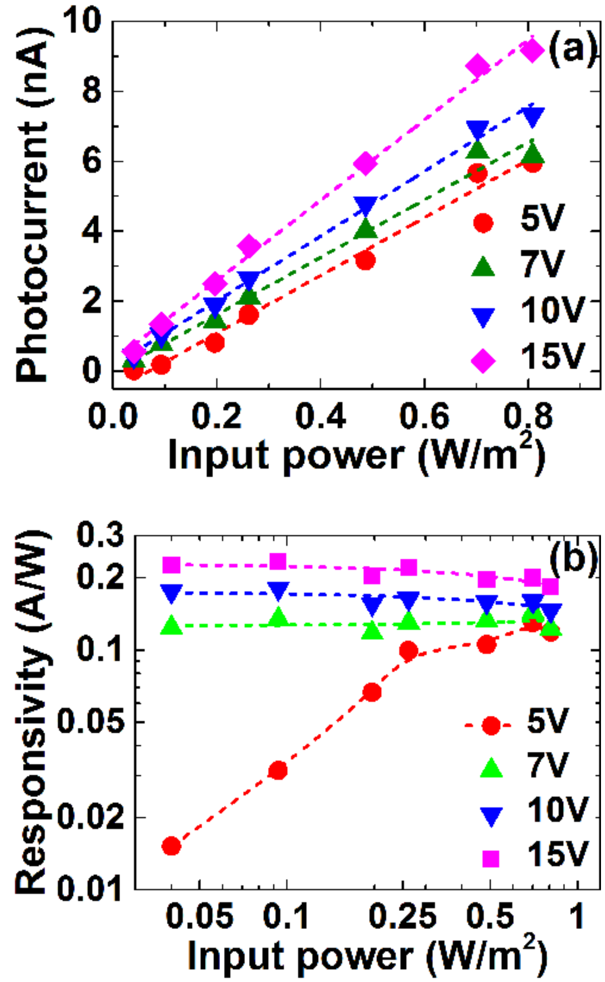

Fig. 5. (a) and (b) shows the photocurrent and responsivity of the MSM photodetector as a function of input power at various applied biases.

The increase of responsivity with the incident power has been attributed to the presence of gain due to the existence of negatively charged trap states at the metal /semiconductor interface [16], [33]. The observation of almost a flat responsivity as a function of input power for applied biases beyond 7 V can be attributed to the saturation of the trap states with holes, resulting in a fixed Schottky barrier and photocurrent. However, at the applied bias of 5 V, the increase in the responsivity with the input power can be attributed to presence of gain due to the non-saturation of these trap states with holes. At lower applied bias and at lower incident power, the number of holes that drift towards the metal contact may not be sufficient enough to saturate the trap states. With more holes available with the increase of input power, the holes filling the trap states also increase, which eventually decreases the Schottky barrier height and creates a gain in the device as a function of input power. However, in the case of applied bias at 5 V and for input powers beyond $\sim$ 0.25 W/m^2, the generated hole density is again sufficient enough to saturate the trap states resulting in a constant gain, and hence almost a flat photo responsivity as a function of input power. It is worth noting that the trapping of electrons in the MSM device at the dislocations also result in the modulation of conductance and drop in the responsivity with applied input power [34]. Moreover, It was also observed that such an effect was amplified in the devices with smaller dimensions [34]. But, the device reported in this report did not suffer hugely with electrons trapping and hence resulted in almost flat responsivity curves. Overall, GaN MSM detectors fabricated over ammonia-MBE grown GaN on Si substrate showed a responsivity of 0.183 A/W and EQE of ~70% at an applied bias of 15V. Moreover, the detectors exhibited good linear detection characteristics with almost a flat responsivity.

IV. Conclusion

For the fabrication of GaN UV detectors, a simple epilayer structure with a GaN thickness of 600 nm was grown on 100-mm Si (111) substrate using ammonia-MBE growth technique. The grown epilayer structure on Si(111) resulted in crack-free GaN with good surface morphology and optical quality. MSM photodetectors with interdigitated contacts showed a low dark current of 0.45 nA at 15 V and demonstrated a good Schottky barrier height of 0.902 eV. The devices exhibited an UV peak responsivity of 0.183 A/W at 15 V with high EQE of 70% and UV/Vis. rejection ratio of ~170. The devices also showed linear characteristics with input power of incident light and presented almost flat responsivity characteristics when the applied bias $\geq$ 7 V.

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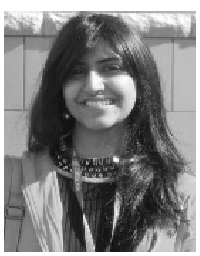
He is currently a Senior Research Scientist with Temasek Laboratories@NTU, Nanyang Technological University, Singapore. His current research is epitaxial growth of III-V nitrides.

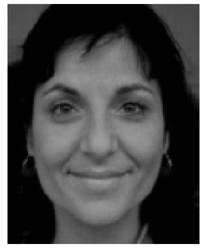


Manvi Agrawal (M'14) received the B.Tech. degree in electronics and communication engineering from the Mody Institute of Technology, India, in 2008, and the Ph.D. degree from the School of Electrical and Electronics Engineering, Nanyang Technological University, Singapore, in 2013.

She is currently a Research Scientist with Temasek Laboratories, Nanyang Technological University, where she is involved in the growth and characterization of GaN-based heterostructures on Si(111), sapphire and SiC substrates by plasma assisted molecular beam epitaxy (MBE), and ammonia-MBE for high frequency and high power applications.

Zilong Wang received the B.S. degree in physics from Peking University, Beijing, China, and the Ph.D. degree in physics from Nanyang Technological University, Singapore, in 2010 and 2016, respectively.

His research interests include the both ultrafast and steady-state spectroscopy and optoelectronics properties of organic semiconducting materials, plasmonics and metamaterials, and low dimensional materials, such as two-dimensional materials, topological insulators and other nanoscale material systems.



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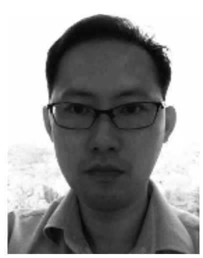
Cesare Soci received the Laurea and Ph.D. degrees in physics from the University of Pavia, Italy, in 2000 and 2005. He was a Post-Doctoral Researcher with the Center for Polymers and Organic Solids, UC Santa Barbara from 2005 to 2006, and the ECE Department, University of California at San Diego, San Diego, from 2006 to 2009. He joined Nanyang Technological University in 2009, where he currently leads the Optical Spectroscopy of Nanomaterials Laboratory, and co-directs the Center for Disruptive Photonic Technologies.

His research encompasses optical materials for photodetection, photovoltaic energy conversion, light emission, and nanophotonic applications.

Tng Lihuang received the B.E. degree in electrical engineering from the University of Newcastle, Australia (external program), in 2010.

Her current area of research is in III-V materials fabrication and characterization.



Kian Siong Ang received the B. Eng. and M.Eng. degrees from Nanyang Technological University, Singapore, in 1997 and 1999, respectively. From 1998 to 1999, he was involved in 0.25μm GaAs-based PHEMT for low noise and high-power MMIC applications for his M.Eng. degree.

From 1999 to 2009, he was with Chartered Semiconductor Manufacturing (CSM) in both technical and management positions. He was leading the F2 Lithography Process Team to excel in engineering fields and process improvement for cost saving, improving yield and fab capacity. He held management position as a MTDC Laboratory Manager. He joined Denselight Semiconductor Pte Ltd., where he developed InP-based HBT MMIC for ultra high speed wireless and optical products from 2001 to 2002. In 2009, he joined Temasek Laboratories, Nanyang Technological University. He has authored or co-authored a few technical papers and patents. His current research interests include III-V compound semiconductor fabrication technology and characterization such as GaN-based MMIC, CMOS compatible GaN-on-Si HEMT and MMIC, InP UV detector, and GaAs based high-power laser and ceramic RF filter. He received many awards and commendations in CSM especially on interfab lithography capacity improvement, F2 capacity ramp and optical color filter for CMOS image sensor.