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2016

Wang, B., Wang, C., Lee, K. H., Bao, S., Lee, K. E. K., Tan, C. S., . . . Michel, J. (2016). Red InGaP light-emitting diodes epitaxially grown on engineered Ge-on-Si substrates. *Light-Emitting Diodes: Materials, Devices, and Applications for Solid State Lighting XX*, 9768, 97681J-. doi:10.1117/12.2211562

<https://hdl.handle.net/10356/90207>

<https://doi.org/10.1117/12.2211562>

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Red InGaP light-emitting diodes epitaxially grown on engineered Ge-on-Si substrates

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ABSTRACT

The integration of light emitting devices on silicon substrates has attracted intensive research for many years. In contrast to the InGaN light emitting diodes (LEDs) whose epitaxy technology on Si substrates is robust and mature, the epitaxy of other compound semiconductor light emitting materials covering the visible wavelength range on Si is still challenging. We have studied epitaxial growth of red InGaP light emitting materials on engineered Ge-on-Si substrates. Ge-on-Si was grown on 8" Si substrates in a metal organic chemical vapour deposition (MOCVD) reactor using two-step growth and cycling annealing. Threading dislocation densities (TDDs) were controlled to as low as $10^6/\text{cm}^2$ by using As-doped Ge initiation. A GaAs buffer layer and lattice-matched InGaP LEDs were grown on the Ge-on-Si sequentially in the same MOCVD process and red LEDs are demonstrated. InGaP multiple-quantum-well LED structures were grown on full 8" Ge-on-Si substrates and characterized.

Keywords: InGaP LEDs, Ge-on-Si substrate, MOCVD epitaxy

1. INTRODUCTION

The integration of light emitting devices on silicon substrate has been an important topic for a long time. Many applications such as lighting, display, sensing, and on-chip optical interconnections need light sources on silicon substrate, which has not been fully realized yet. The fundamental difficulties come from the inability of light emission of Si itself and the epitaxy of direct bandgap III-V semiconductors on Si. The InGaN light emitting diode (LED) is an exception among III-V semiconductors because the epitaxy on Si substrate is robust and mature and utilized in applications for high brightness LEDs¹. However, the nitride LEDs only provide blue or shorter wavelengths for visible light emission. For longer wavelengths, nitride LEDs are not suitable due to the large bandgap². Another problem is that the epitaxy of InGaN LEDs can only take place on (111) Si substrate and this would add difficulties for some applications that require integration with CMOS. Therefore it is still important to develop AlGaInP LEDs on Si substrates to cover the red and yellow-green wavelength range. AlGaInP LEDs are usually grown on lattice-matched GaAs substrates and to bridge the lattice-mismatch with Si, buffer layers have to be inserted between the III-V LED and Si substrate³. Ge is a good candidate as the buffer. Together with the development of GaAs epitaxy on close lattice-matched Ge (~0.08% mismatch) and compositional graded Ge/GeSi on Si, LEDs and lasers based on AlGaAs/GaAs and InGaAs/GaAs have been demonstrated on Si substrates in the past⁴⁻⁹. On one hand the threading dislocation density (TDD) of Ge/GeSi substrate can be controlled to the level of $10^6/\text{cm}^2$; on the other hand, optimized GaAs epitaxy on Ge substrate does not create extra dislocation or anti-phase domain defects and this can be used as virtual substrate for lattice-matched arsenide and phosphide compounds^{4,5,9}. AlGaInP LED arrays have been demonstrated on engineered Ge/GeSi substrate and integrated with CMOS³. Due to the thick Ge/GeSi buffer, the integration scheme is still complicated³. It is therefore desirable to develop InGaP LEDs on direct grown Ge-on-Si substrate without the thick compositional-graded GeSi buffers.

In this work, we demonstrate red InGaP LEDs on Ge-on-Si substrates and compare them to LEDs grown on bulk Ge. Direct grown Ge-on-Si substrates have the advantage of thin Ge buffer layers of $\sim 1\ \mu\text{m}$ and smooth surfaces (surface roughness $< 1\ \text{nm}$)^{10,11}, while the drawback is the relatively high TDD level of $\sim 10^7/\text{cm}^2$. By adding As dopant in the initiation stage of Ge epitaxy on Si, the TDD level was successfully reduced to $\sim 10^6/\text{cm}^2$, one order of magnitude lower than regular Ge-on-Si¹¹. The p-i-n InGaP LED grown on the As-doped Ge-on-Si substrate shows stronger electroluminescence (EL) than the same LED grown on a regular Ge-on-Si substrate. Multiple-quantum-well (MQW) InGaP LED structures grown on full 8'' Ge-on-Si wafer show good photoluminescence (PL) wavelength uniformity. These preliminary results indicate that it is promising to develop visible LEDs on Si substrate by using Ge-on-Si substrates.

2. EXPERIMENTAL

Figure 1 shows the schematic drawings of the layer stacks of the LEDs grown on top of the regular and As-doped Ge-on-Si substrates. An Aixtron close-coupled-showerhead MOCVD system is used for the epitaxy of both Ge-on-Si substrates and III-V InGaP LEDs. GeH_4 and SiH_4 are the precursors for the epitaxy of Ge-on-Si. 8'' (100) Si wafers with 6° offcut towards the [110] direction were used as the substrates. Prior to loading the wafers into the MOCVD reactor, standard RCA cleaning followed by HF dip ($\text{HF}:\text{H}_2\text{O}=1:10$) was applied to clean the wafers. After loading the wafer in reactor, high temperature bake ($1050\ ^\circ\text{C}$) was performed in H_2 ambient for 10 mins to drive off any moisture and desorb any residual surface native oxide. A thin layer of homoepitaxy Si was grown to bury surface contamination on the Si substrate. Ge epitaxy was initiated at low temperature of $400\ ^\circ\text{C}$ which serves as a seed layer. After a continuous and smooth Ge seed layer was formed high temperature Ge growth at $650\ ^\circ\text{C}$ was performed. Post-growth annealing was used to accelerate the dislocation gliding. A special method of adding As-dopant in the Ge seed layer was used to decrease the TDD level further¹¹. In this sample AsH_3 was flowed into the chamber together with GeH_4 in the initiation stage. When the high temperature Ge growth was started the AsH_3 flow was gradually decreased until fully stopped and regular Ge growth was continued. More detailed description of the Ge-on-Si substrate preparation can be found in Reference 11. The typical TDD level of Ge-on-Si without As-doping is $\sim 5 \times 10^7/\text{cm}^2$ while a similar wafer including As-doping has lower TDD level of $5 \times 10^6/\text{cm}^2$. Both the As-doped and undoped Ge-on-Si wafers have surface roughness of less than $1\ \text{nm}$.

InAlP/InGaP/InAlP p-i-n LEDs lattice-matched with GaAs were grown on bulk Ge, regular Ge-on-Si, and As-doped Ge-on-Si substrates (small pieces) in one growth. The layer stacks of the LEDs and the different Ge-on-Si substrates are showed in Figure 1 (a) and (b). GaAs buffer layers of about $1.4\ \mu\text{m}$ -thick were initiated on the bulk Ge and Ge-on-Si substrates by using our optimized GaAs-on-Ge conditions, with TMGa and AsH_3 sources, where details can be found in Reference 9. The InAlP/InGaP LEDs were grown at $630\ ^\circ\text{C}$ and 100 mbar by using TMGa, TMIIn, TMAI, and PH_3 . DMZn and DETe were used for p- and n- type doping. The p-type doping concentration was targeted at $5 \times 10^{17}/\text{cm}^3$ and n-type at $2 \times 10^{18}/\text{cm}^3$. The thicknesses of p-InAlP, i-InGaP, and n-InAlP are 500 nm, 300 nm, and 300 nm, respectively. Finally, a 100 nm-thick p-GaAs layer doped by Zn was used to cap the p-InAlP as the contact layer and to protect the InAlP layer from oxidization. Ni/Ge/Au metal was used as n-contact on n-type GaAs buffer, and Ti/Au was used as p-contact and deposited on etched mesa, followed by lithography and lift-off to form the LEDs.

After successful LED operation was demonstrated, InAlGaP/InGaP multiple-quantum-well (MQW) LED structures were grown on full 8 inch (200 mm) regular Ge-on-Si substrates to improve the LED efficiencies. Te-doped 270 nm-thick $\text{In}_{0.48}\text{Al}_{0.52}\text{P}$ was used as the n-type layer and Zn-doped 350 nm-thick $(\text{In}_{0.5}\text{Al}_{0.5})_{0.49}\text{Ga}_{0.51}\text{P}$ was used as p-type layer. The InAlGaP barrier thickness is targeted at 100 nm and InGaP well thickness is targeted at 20 nm. Transmission Electron Microscopy (TEM), wafer bowing, X-ray Diffraction Reciprocal Space Mapping (XRD-RSM), and PL mapping were performed to study the structural and uniformity properties.

Figure 1. (a) InAlP/InGaP LED on regular Ge-on-Si; (b) InAlP/InGaP LED on As-doped Ge-on-Si.

3. RESULTS AND DISCUSSIONS

Figure 2 (a) shows the current-voltage (I-V) curves of the InGaP LEDs grown on Ge, As-doped Ge-on-Si, and regular Ge-on-Si substrates. All LEDs have the same mesa size of $1\text{mm} \times 1\text{mm}$. The LEDs on the As-doped Ge-on-Si and bulk Ge have almost identical I-V curves. The reverse bias current of the LED on regular Ge-on-Si is more than four orders of magnitude higher. In forward bias before the turn-on voltage the current is also much higher for the LED on regular Ge-on-Si. Above the turn-on voltage the current gradually approaches that of the other two LEDs. The reason may be related to the substrates defect levels, device fabrication, and repeatability. The details are being studied. Figure 2 (b) shows the electroluminescence (EL) spectra of the three LEDs at a constant drive current of 150 mA. The EL intensity of the LED on bulk Ge substrate is 7.8 times higher than the LED on As-doped Ge-on-Si and 19.6 times higher than the LED on regular Ge-on-Si. The EL peak wavelength of the LED on bulk Ge is at 654 nm while the peak wavelength for the other devices is at 656 nm. Although none of the LEDs made on (As-doped) Ge-on-Si substrate is as good as the LEDs made on bulk Ge substrate, it is clearly demonstrated that the LED on As-doped Ge-on-Si has better performance than the one on regular Ge-on-Si.

Figure 2. (a) Current-voltage curves of InGaP LEDs on Ge substrate, As-doped Ge-on-Si, and regular Ge-on-Si substrates; (b) EL spectra of the InGaP LEDs at injection current of 150 mA.

Figure 3 (a) shows a schematic layer stack drawing of the InGaP MQW LED on 8'' Ge-on-Si wafer. A cross-sectional TEM image of the InGaP MQWs is shown in Figure 3 (b). No defects are observed in the MQW region or the p- and n-type layers. The InAlGaP barriers are 110 nm thick and the InGaP quantum wells are 22 nm thick. Very few defects are observed in the GaAs buffer layer and high-T Ge layer. The only defects-dense area is in the Ge seed layer on the Si substrate. The TEM indicates overall good epitaxy quality of the MQW LED structure on the Ge-on-Si wafer.

While the TEM imaging indicates rare defects and good epitaxy quality, the wafers are bowed after cooling from the growth temperature to room temperature due to the large thermal expansion mismatch between III-V and Si. The sample having a 2.2 μm GaAs buffer has concave wafer bowing of 160 μm . By decreasing the GaAs buffer to about 500 nm and keeping all the other layers the same thickness, the wafer bowing is decreased to 120 μm . This is still too large to be processed for example by either stepper lithography or wafer bonding which typically require less than 50 μm bowing. On the other hand, reducing the GaAs buffer thickness to decrease bowing may worsen the auto-doping effect between GaAs and Ge which may eventually affect the device performance. Consistent with the wafer bowing, XRD-RSM measurements (data not shown) show the wafer having a 2.2 μm -thick GaAs buffer has $\sim 0.2\%$ tensile strain accumulated in both the Ge and GaAs buffer layers. To overcome the wafer bowing problem both the layer thickness and growth temperature have to be optimized.

Figure 4 (a) shows the PL intensity mapping at the peak wavelength of 650 nm of the wafer having a 500 nm-thick GaAs buffer. The intensity variation is less than 20%. In the center of the wafer there is a bright ring region that coincides with the heater zone A. Temperature variation of a few degrees may induce a small variation of the growth rate and this may eventually convert to the layer thickness variation. Figure 4 (b) shows the PL peak wavelength mapping, with a variation of about 1.8 nm across the entire 8'' wafer. This indicates very good PL wavelength uniformity despite the PL intensity variation.

Figure 3. (a) Lay stack drawing of the InAlGaP/InAlP MQW LED on 8'' Ge-on-Si wafer, the total thickness of the Ge buffer is about 730nm; (b) TEM image of the InAlGaP/InGaP MQW region. The InAlGaP barrier is 110 nm thick, and InGaP well is 22 nm thick. No defect can be seen in the imaging area.

Figure 4. (a) PL intensity mapping at the peak wavelength of 650 nm, the variation is less than 20%; (b) PL peak wavelength mapping. The variation across the whole wafer is about 1.8 nm.

4. SUMMARY

In summary, we have demonstrated the operation of red InGaP LEDs on Ge-on-Si substrates. The LEDs on As-doped Ge-on-Si have higher EL intensity than the LEDs grown on regular Ge-on-Si and the leakage current is several orders of magnitude lower. Improvements in epitaxy and processing should generate better device performance. InGaP MQW LED structures grown on 8" Ge-on-Si wafers show large wafer bowing and good PL wavelength uniformity. This study indicates that the integration of InGaP LEDs on Si substrate is achievable and that it will eventually enable integrated light emitters on Si.

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