AlGaInP Microcavity Light-Emitting Diodes at 650 nm on Ge Substrates

P. Modak, M. D'Hondt, D. Delbeke, I. Moerman, P. Van Daele, R. Baets, P. Demeester, and P. Mijlemans

***Abstract*—We demonstrate microcavity light emitting diodes (MCLEDs) emitting at 650 nm on Ge substrates. Ge has the advantage of lower cost and higher strength compared to GaAs substrates. The multi-quantum well microcavity devices consisted of AlGaAs-based distributed Bragg reflector (DBR) mirrors, AlGaInP active material with an additional 5-μm p-$Al_{0.55}Ga_{0.45}As$ current spreading layer on top of the p-DBR. A maximum external quantum efficiency of 4.35% and an optical power higher than 5 mW was obtained for a device with 200-μm diameter. The results indicate the potential use of MCLEDs on Ge for visible LEDs.**

***Index Terms*—AlGaInP, Ge, light emitting diode, microcavity.**

I. Introduction

EMISSION at visible wavelengths is useful for car tail and brake lights, traffic lights, full color LED displays, scanners, printers, high-definition televisions and short-haul plastic optical fiber communication which has a low absorption near 650 nm [1]. Microcavity LEDs (MCLEDs) are of importance for their enhanced spontaneous emission and narrow linewidth compared to conventional LEDs and for their circular beam output and low beam divergence [2]. MCLEDs employ an active region placed inside a Fabry–Perot cavity. One mirror normally has a high reflectivity while the other may be varied to obtain the desired device performance.

AlGaInP-based visible MCLEDs using AlAs–AlGaAs distributed Bragg reflectors (DBR) [3] or AlGaInP alloy-based DBRs [4] have been previously reported, both using GaAs substrates. Within this work we investigate whether germanium wafers can serve as a growth substrate for these materials. It is commonly known that most part of the world-wide commercial MOVPE-growth is performed on Ge, namely for the production of solar cells [5], where nearly the same performance is obtained as on GaAs substrates. Germanium indeed offers some advantages: the substrates are significantly cheaper and have almost the same lattice constant compared to the GaAs. Further Ge is mechanically stronger, which allows the substrates to be made thinner (e.g., 140 μm for 100-mm wafers). Also, Ge-substrates up to 150 mm, exhibiting zero etch pit density have already been demonstrated.

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However, there are a few growth related issues for GaAs on Ge, that have to be overcome in order to achieve high-quality material and devices. Ge is nonpolar in nature, while GaAs is polar which can result in the formation of anti-phase domains (APDs). The APDs influence the charge neutrality in the crystal, thus affecting the electrical properties of the device. Also the germanium diffusing into the epi-layers is often addressed as a possible hazard. Further the differences in lattice constant and thermal expansion coefficient can lead to the formation of misfit dislocations, which degrade the material quality and which can severely affect the electrical and optical performances of the device.

If all these problems could be tackled, the germanium would definitely become the substrate of choice. First proofs of concept, that Ge is suited as a replacement for GaAs substrates, were the realization of high-quality InGaAs–AlGaAs LEDs and laser diodes [room temperatrure (RT) and continuous wave (CW)] reported before [6]. Also, we have previously shown the feasibility of AlGaInP nonresonant LEDs on Ge [7]. In this paper, we report on MCLEDs emitting at 650 nm using AlGaInP-based active material and AlGaAs-based DBR mirrors on Ge substrates.

II. Growth and Fabrication

The epitaxial layers were grown in a Thomas Swan close-spaced vertical MOVPE reactor at 76 Torr and mainly at 730°C on a 3-in n-type Ge substrate. The DBR mirrors consisted of $Al_{0.95}Ga_{0.05}As$ and $Al_{055}Ga_{0.45}As$ layers, 26.5 periods Si-doped at the bottom, five periods Zn-doped at the top [Fig. 1(a)]. The layers forming the top DBR had linearly graded interfaces (~10 nm) to reduce the series resistance. The active layer consisted of three compressively strained 5-nm $Ga_{0.44}In_{0.56}P$ quantum wells with $(Al_{0.5}Ga_{0.5})_{0.52}In_{0.48}P$ as both barrier and spacer layer. The spacer layers were doped with Si and Mg on the n and p sides respectively. A 5-μm-thick p-$Al_{055}Ga_{0.45}As$ ($\sim 1 \times 10^{18}$ cm^{-3}) current spreading layer was grown on top of the p-DBR. The active layer thickness corresponded to a 1-lambda cavity with 8-nm detuning. A thin ~5-nm highly Zn doped p-GaAs ($\sim 1 \times 10^{19}$ cm^{-3}) layer was grown on top as the contact layer. A reference LED was also grown without any DBR mirrors but including the same 5-μm-thick p-$Al_{055}Ga_{0.45}As$ current spreading layer [Fig. 1(b)]. The samples were processed by forming isolation mesas by H_2SO_4-based wet chemical etching. Ti–Au was used as the p-type contact and AuGe–Ni as the back side contact. The top-contact was electroplated with Au to improve series resistance and strength. Devices were made with 100-μm and 200-μm diameters, including a grid-like metal contact pattern inside the apertures to improve current spreading [Fig. 1(c)].

III. Results and Discussion

Fig. 2 shows the reflection spectrum from a calibration run which consisted of 15.5 periods of $Al_{0.95}Ga_{0.05}As$–$Al_{0.55}Ga_{0.45}As$ layers with 196 nm of $(Al_{0.5}Ga_{0.5})_{0.52}In_{0.48}P$ on top forming a 1-lambda cavity at 650 nm. The reflection spectrum has a dip near 650 nm confirming the growth velocity of the spacer layer with high accuracy.

RT electroluminescence measurements were carried out in CW mode. The optical power versus current emitted by a 200-μm device is shown in Fig. 3. The devices exhibit an optical power of 4 mW at 80 mA and saturate above this current. The maximum external quantum efficiency obtained was 4.35% at 10 mA. Similarly, a maximum external quantum efficiency of 3.6% was measured at 4 mA for a 100-μm device. All the devices show a high forward voltage of more than 5 V at 20 mA. The high forward voltage may be due to two factors. Fig. 4(a) shows the I–V curve for the 200-μm MCLEDs that contains an $Al_{0.95}Ga_{0.05}As$–$(Al_{0.5}Ga_{0.5})_{0.52}In_{0.48}P$ interface and also the reference LED which has an interface formed by $Al_{0.55}Ga_{0.45}As$ and $(Al_{0.5}Ga_{0.5})_{0.52}In_{0.48}P$ layers. The current was measured for both increasing and decreasing voltages, indicating an hysterisis effect for the MCLED. The hysterisis effect is, however, absent in the reference LED. This suggests that the problem lies at the interface between the top $(Al_{0.5}Ga_{0.5})_{0.52}In_{0.48}P$ and the first $Al_{0.95}Ga_{0.05}As$ DBR layer, acting as a barrier to the electrical carriers. It has been found experimentally that this problem can be solved by either increasing the Al-fraction in the AlGaInP or by decreasing Al in the AlGaAs forming the hetero-interface. The second reason for the high forward voltage is the Ti–Au contact on top of $Al_{0.55}Ga_{0.45}As$ material (covered with 5-nm p^+-GaAs). It appears that this combination results in a Schottky like behavior, leading to high series resistance and poor current spreading through the grid. Tests have indicated that Au–Zn contacts do exhibit ohmic behavior and that they give us a significantly reduced forward bias. As shown in Fig. 4(b), with a Au–Zu top contact, the forward voltage for the reference LED is about 2 V while that of the MCLED (the hysterisis effect still exists) is 2.7 V at 20 mA.

The differential resistance for both structures is however very similar, 13 Ω for the reference LED and 13.7 Ω for the MCLED, indicating that the DBRs in the MCLED do not contribute significantly to the series resistance. The difference in the turn-on voltage is thus almost entirely caused by the problem at the layer interface. This implies that it should be possible to operate red MCLEDs on Ge substrates at 20 mA when biased with 2 V. As shown in Fig. 2, for the Au–Zu top contact, the output power has also increased to 5 mW at 80-mA current. The optical output power and efficiency from our MCLEDs on Ge substrates compare well to other reported results for MCLEDs on GaAs substrates [3].

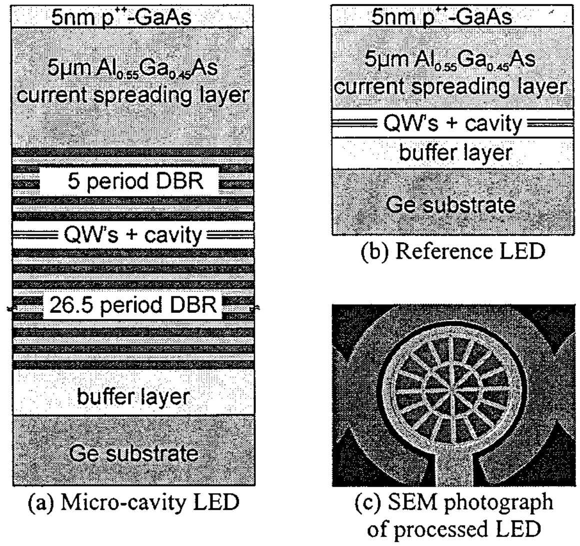

Fig. 1. Structure of a MCLED and a reference LED used in this study.

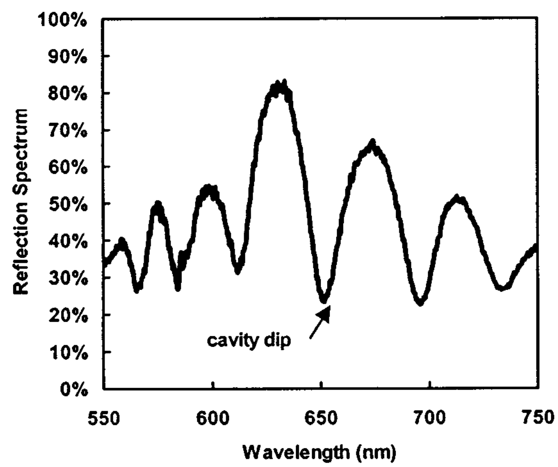

Fig. 2. Reflection spectrum from a calibration run.

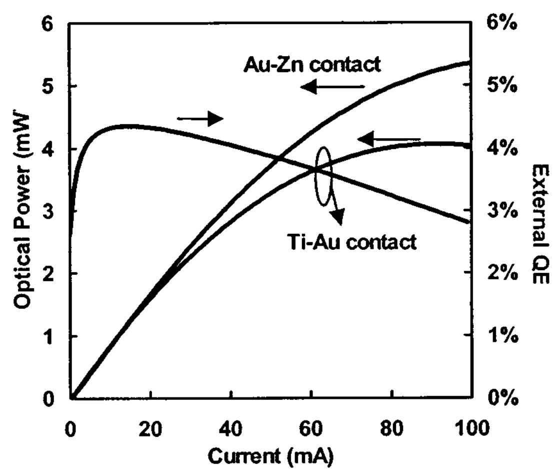

Fig. 3. Optical power and external quantum efficiency for a 200-μm-diameter device.

The use of thick current spreading layer that enables better current injection however introduces extra resonance modes in the MCLED (Fig. 5). The extra resonance modes can be suppressed with the application of a single layer antireflection

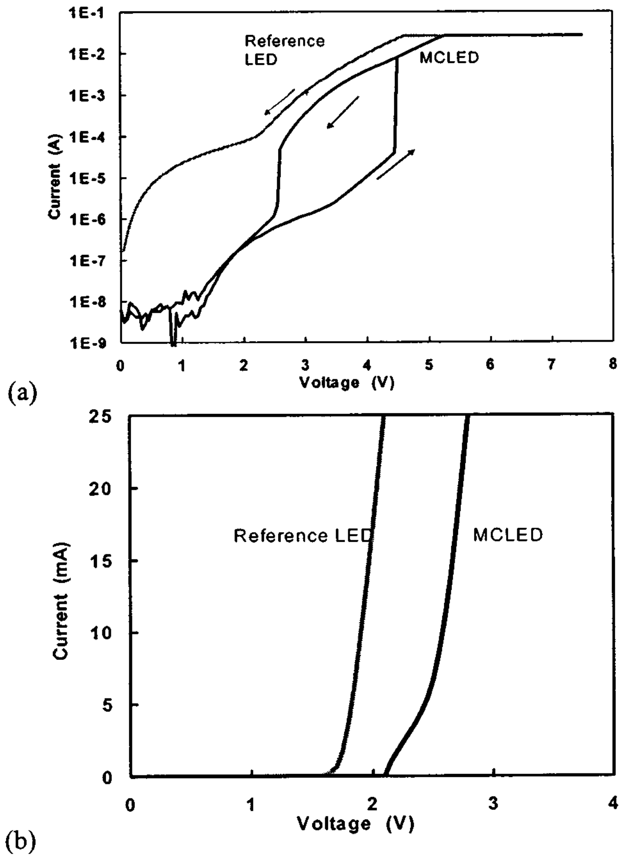

Fig. 4. I–V characteristics showing forward voltage for the MCLED (thick line) and reference LED (shadow line) with (a) Ti–Au top contact and (b) Au–Zn top contact. The MCLED exhibits an hysterisis effect.

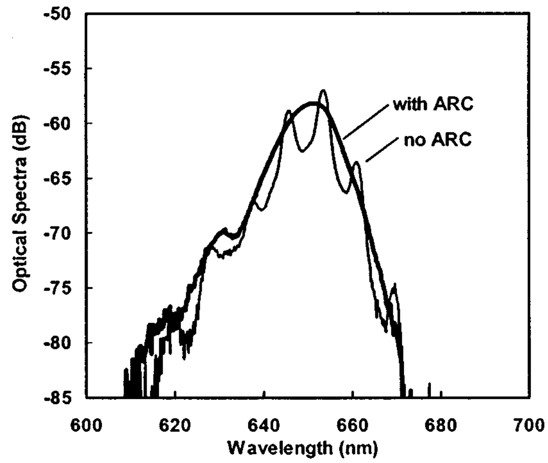

Fig. 5. Optical spectra from a 200-μm-diameter device at 20 mA with a current spreading layer, with and without an anti-reflection coating.

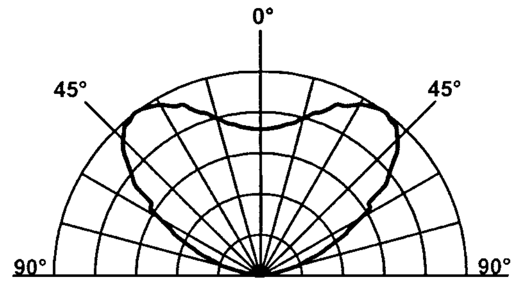

Fig. 6. Measured far-field radiation pattern from a 200-μm-diameter device with a current spreading layer.

coating (ARC). The material used was hafnium dioxide (HfO_2) with a refractive index of 1.8 and a thickness of 95 nm. Due to the ARC, as shown in Fig. 5, the spectrum exhibits a single node shape with the peak at 652 nm and a full-width half-maximum of 13 nm. The peak shifts to longer wavelengths with increasing current. This is primarily caused by a change of the optical cavity length due to the temperature dependence of the refractive index [3] and less to the temperature dependence of the quantum well emission.

Fig. 6 shows the far field radiation pattern from a 200-μm device. The pattern shows lobes at about 36° from the normal direction. These emission patterns can be altered by a different tuning of the cavity thickness, which will of course also influence the total emitted power.

IV. Conclusion

We have demonstrated AlGaInP-based MCLEDs on Ge. Devices with a current spreading layer exhibited 4.35% external quantum efficiency at 10 mA and more than 5 mW at 80-mA current. Deposition of an antireflection coating eliminates the multiple nodes from the optical spectrum of such devices. The electrical and optical performance of our MCLEDs on Ge are comparable to the best reported on GaAs substrates. These results suggest that LEDs in general can be as good on Ge as on GaAs, and further the results indicate that MCLEDs can give decent performance in the visible for fairly easy processing with single facet emission. Further device and process optimization is in progress to obtain increased quantum efficiency and reduced threshold voltage.

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