High Efficiency InAlGaP Microcavity LEDs on Ge-substrates

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

[a] Department of Information Technology, University of Gent/IMEC, Sint-Pietersnieuwstraat 41, B-9000 Gent, Belgium
[b] Union Minière- Business Group Advanced Materials, Kasteelstraat 7, B-2250 Olen, Belgium

We have studied the feasibility of Ge-substrates to replace GaAs for LED applications. Ge is a very promising substrate because of its lower cost, higher mechanical strength, lower etch pit density, similar lattice constants and potential for larger diameters when compared to GaAs. InAlGaP layers grown by MOVPE on Ge substrates exhibited good crystalline and optical quality. The InAlGaP-epilayers showed excellent uniformity on photoluminescence wavelength and intensity. The unpackaged InAlGaP microcavity LEDs on Ge emitting at 638nm exhibited an efficiency of 5.23% at 4mA, an optical output power of about 8mW at 100mA promising its potential outdoor applications.

Introduction

Due to the success of germanium wafers for the production of solar cells for satellite power supply, Ge has substantial use in the world of MOVPE. Ge has a similar lattice constant as GaAs, but offers some advantages compared to GaAs such as lower cost, higher mechanical strength, lower etch pit density and a somewhat higher thermal conductivity. This makes Ge also a valuable candidate to replace GaAs for applications other than solar cells. Previously, we have already reported on the successful implementation of (In)(Al)GaAs-based 850 nm and 980 nm LEDs and laser diodes on Ge-substrates[1].

In this paper we focus on LEDs emitting at visible wavelengths, 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. Microcavity LEDs have a great potential since these do not require complex and expensive processing. Additionally, MCLEDs can exhibit a narrow spectral linewidth and low beam divergence[2]. The working principle is based on a Fabry-Perot resonance, for an active region placed inside a cavity formed by one highly and one medium reflective mirror. By detuning the cavity, which means deviating from the exact n-lambda dimensions, it is possible to further enhance light extraction.

AlGaInP based visible micro-cavity LEDs using AlAs-AlGaAs DBRs[3] or AlGaInP based DBRs[4] have been previously reported by others, both using GaAs substrates. In this paper, we demonstrate the feasibility of Ge-substrates for high-efficiency InAlGaP micro-cavity LEDs emitting at 638nm. More details on these InAlGaP MCLEDs on Ge can be found elsewhere[5][6].

Experimental details

All the layers are grown by means of metal-organic vapor phase epitaxy in a Thomas Swan vertical closely spaced rotating disc reactor on 3inch n-type Ge substrates, supplied by Union Minière. The precursors are tri-methyl indium (TMI), tri-methyl Gallium (TMG),

[1] Corresponding author: Tel.: +32-9-264-3316, Fax: +32-9-264-3593, e-mail: prasanta.modak@intec.rug.ac.be

tri-methyl aluminum (TMA), pure PH_3 and pure AsH_3. SiH_4 is used as n-dopant, Cp_2Mg is used for p-doping of InAlGaP and DEZ for p-doping of (Al)GaAs-layers. All device layers are grown at a pressure of 76 Torr and mainly at a temperature of 730°C. For the MCLED device structure, the individual layers were grown and calibrated for optimum uniformity and performance.

All MCLEDs in this study have a layer structure similar to the one presented in Fig.1(a&b). The devices have a structure with 3 compressively strained (Al)GaInP quantum wells, embedded within detuned 1-lambda cavity. $(Al_{0.7}Ga_{0.3})_{0.52}In_{0.48}P$ is used as both barrier and spacer layer that forms the cavity. The Si-doped bottom DBR consists of 26.5 periods of $Al_{0.55}Ga_{0.45}As$ and AlAs. The Zn-doped top DBR consists of 5 periods of $Al_{0.55}Ga_{0.45}As$ and $Al_{0.95}Ga_{0.05}As$, but has linearly graded interfaces (10nm) to improve the series resistance. On top of the p-DBR we have used 3µm thick $Al_{0.55}Ga_{0.45}As$ ($p \sim 1x10^{18}$ cm^{-3}) as current spreading layer. An additional 10nm of GaAs ($p \sim 1x10^{19}$ cm^{-3}) was grown on top to improve series resistance and to prevent oxidation.

The devices have been processed to mesa-type LEDs, which are etched through the current spreading layer and the top DBR. The top contact for the devices is Au-Zn and the backside contact to Ge is AuGe/Ni. The top-contact is electroplated with Au to improve series resistance and strength. Devices have been made with 250µm square shape apertures including metal contact patterns inside it to improve current spreading (Fig.1c).

InAlGaP-layers on Ge-substrates

Ge has a slightly higher lattice constant (5.6575Å) compared to GaAs (5.6533Å). For the optimisation of the InAlGaP layers, it is therefore important that the In-fraction of the (Al)GaInP material is slightly increased when growing on Ge-substrates. In Fig.2, we show a DCXRD rocking curve where one can observe the layer peaks from the Ge-substrate, the GaAs buffer and the AlGaInP layer, the latter being slightly compressively strained to the Ge.

InAlGaP materials further are quite sensitive to growth temperature, because of temperature dependent In-incorporation. By tuning the temperature distribution inside the reactor, it was possible to obtain good uniformity on PL wavelength and intensity. In Fig.3, we show the PL-mapping of InGaP/InAlGaP QWs on a 3-inch Ge-wafer. The standard deviation on the average peak wavelength (641nm) is only 0.6nm. The full width at half-maximum average is 16.9nm while the standard deviation is 0.4nm.

Because of the cavity resonance principle in the MCLEDs, it is crucial to have good control on growth velocity of both DBR and cavity (i.e. spacer layers). Therefore, we performed a calibration run which consisted of 15.5 periods of AlAs/ $Al_{0.55}Ga_{0.45}As$ layers, with 202nm of $(Al_{0.7}Ga_{0.3})_{0.52}In_{0.48}P$ on top, forming a 1-lambda cavity at 640nm between the air and the DBR. The reflection spectrum (Fig.4) has a dip near 640nm confirming (with high accuracy) the right growth velocity for the spacer layer. The same spectrum also provides necessary information regarding the DBR peak position.

InAlGaP MCLEDs on Ge-substrates

The optical power and external quantum efficiency versus current for MCLEDs emitting at 638nm with a p-$Al_{0.55}Ga_{0.45}As$ current spreading layer are shown in Fig.5. The optical power reaches 8mW at 100mA and the maximum external quantum efficiency is 5.23% at 4mA which is much higher than those obtained from conventional non-resonant LEDs[7][8].

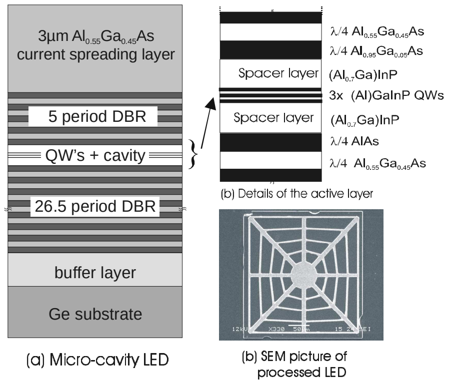

Figure 1 Shows MCLED structure and metal grid on the device.

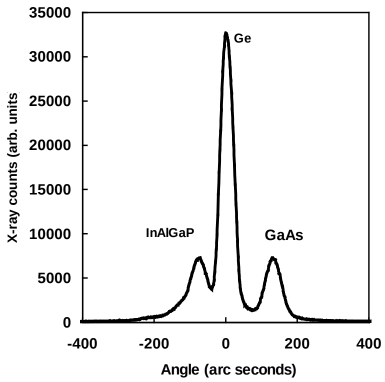

Figure 2 DCXRD curve of InAlGaP on GaAs-buffer layer on Ge.

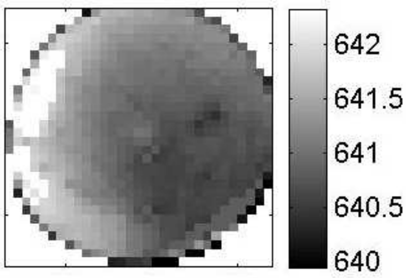

Figure 3 PL wavelength mapping of InGaP/InAlGaP QWs at 641nm on a 3-inch Ge-wafer.

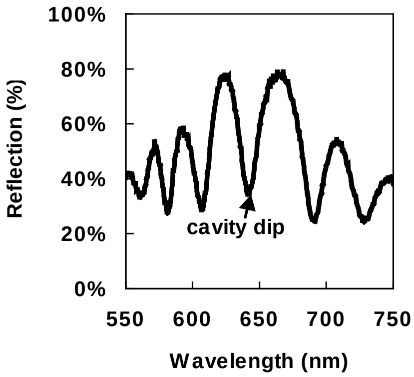

Figure 4 Reflection spectrum from a calibration run for DBR and spacer layers.

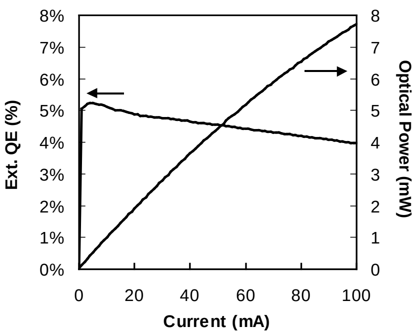

Figure 5 Optical power and external quantum efficiency for MCLEDs emitting at 638nm with p-$Al_{0.55}Ga_{0.45}As$ current spreading layer.

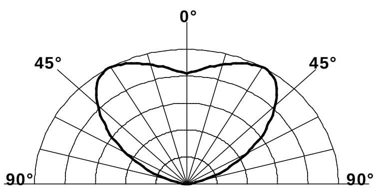

Figure 6 Measured far-field radiation pattern from devices emitting at 638nm showing the effect of cavity detuning. Maximum intensity occurs at an angle of 30° when viewed from the normal direction.

In Fig.6, we show the far field radiation pattern from the MCLEDs. We can clearly see the position of the maximum intensity lobes at 30° from the normal viewing direction for the 638nm MCLED confirming the micro-cavity effect present in the devices.

Conclusion

We have demonstrated the MOVPE growth of very uniform InAlGaP quantum wells on 3-inch Ge substrates. Microcavity LEDs emitting at 638nm exhibit an external quantum efficiency of 5.23% at 4mA and an output power of 8mW at 100mA. When we compare our results of MCLEDs on Ge substrates to those of MCLEDs on GaAs published by others [3][4], it is clearly demonstrated that also in the visible wavelength region Ge substrates can replace GaAs.
We are even confident that further optimisation of the layer structure will allow further performance improvement of MCLEDs on germanium.

Acknowledgement

The major part of this work was supported by Union Minière and partially funded by IWT (the Institute for the Promotion of Innovation by Science and Technology in Flanders). We also wish to thank Steven Verstuyft and Steven van Put for device processing.

References

[1] M. D'Hondt, Z. Q. Yu, B Depreter, C. Sys, I. Moerman, P. Demeester and P. Mijlemans, "High quality InGaAs/AlGaAs lasers grown on Ge substrates", J. Cryst. Growth, vol. 195, pp. 655-659, 1998.
[2] E. F. Schubert, Y.-H. wang, A. Y. Cho, L.-W. Tu, and G. J. Zydzik, "Resonant cavity light-emitting diode", Appl. Phys. Lett., vol. 60, pp. 921-923, 1992.
[3] K. Streubel, U. Helin, V. Oskarsson, E. Bäcklin and Å. Johansson, "High brightness visible (660nm) resonant-cavity light-emitting diode", IEEE Photonics Tech. Lett., vol. 10, pp. 1685-1687, 1998.
[4] J. A. Lott, R.P. Schneider, Jr., J.C. Zolper and K.J. Malloy, "AlGaInP visible resonant cavity light emitting diodes", IEEE Photonics Tech. Lett., vol. 5, pp. 631-633, 1993.
[5] P. Modak, M. D'Hondt, D. Delbeke, I. Moerman, P. Van Daele, R. Baets, P. Demeester and P. Mijlemans, "AlGaInP Microcavity Light-Emitting Diodes at 650 nm on Ge Substrates", IEEE Photon. Tech. Letters, vol. 12, pp. 957-959, 2000.
[6] M. D'Hondt, P. Modak, D. Delbeke, I. Moerman, P. Van Daele, R. Baets, P. Demeester and P. Mijlemans, "4mW microcavity LED at 650nm on germanium substrates", Photonics West, Jan.22-28, 2000, San Jose, California, and published in the SPIE proceedings, paper number 3938-41.
[7] C. P. Kuo, R. M. Fletcher, T. D. Osentowski, M. C. Lardizbal, M. G. Craford and V. M. Robbins, "High performance visible light-emitting diodes", Appl Phys. Lett., vol. 57, pp. 2937-2939, 1990.
[8] H. Sugawara, M. Ishikawa and G. Hatakoshi, "High-efficiency InAlGaP/GaAs visible light-emitting diodes", Appl Phys. Lett., vol. 58, pp. 1010-1012, 1991.