# High Efficiency Planar Microcavity LED's: Comparison of Design and Experiment

H. De Neve, J. Blondelle, *Member, IEEE,* R. Baets, *Member, IEEE,* P. Demeester, *Member, IEEE,* P. Van Daele, *Member, IEEE,* and G. Borghs

***Abstract*—This paper describes the design of substrate emitting microcavity LED's and a comparison of experimental results with modeling results. The modeling is based on a simulation tool which accounts for guided modes, quantum well reabsorption and photon recycling. The overall quantum efficiencies of $\lambda/2$ and $\lambda$ cavities both with a 60% and a 90% reflecting DBR mirror are compared and a good qualitative correspondence is found between theory and experiment. The maximum theoretical overall quantum efficiency for the considered structures is expected to be around 14%, whereas the best experimental value amounts to 10.2%.**

## I. Introduction

THE introduction of microcavity light emitting diodes has offered the perspective of highly efficient and spectrally narrow semiconductor light sources other than lasers [1]–[6]. In contrast to lasers microcavity LED's do not suffer from any threshold behavior. The increased electrical-to-optical power efficiency as compared to conventional LED's should improve the applicability of these new devices in optical interconnection systems and other power budget critical systems.

Epitaxially grown Fabry–Perot like microcavities have been widely studied both in optical pump experiments and in electroluminescent devices. The latter show an increased spectral power density over conventional LED's and recent work [6] has indicated that the overall efficiency can be much higher than in conventional planar LED's.

The design of planar microcavity LED's optimized towards high external efficiency is far from straightforward. Therefore we implemented a simulation program for planar microcavity LED's, including a calculation of the power conversion efficiency. We introduced some new aspects into the analysis which appear to play a major role in the quantum efficiency (QE) of microcavities. One of them is the existence of guided modes. It was already suggested by other authors [7]–[9] that part of the light is coupled to the guided modes of the structure thereby decreasing the extraction efficiency. Another aspect is the reabsorption of light by the active material, also suggested to be one of the reasons for the low QE of microcavity LED's [5].

This letter presents some principles behind the calculation of the guided modes, the reabsorption of light and the photon recycling mechanism all of which influence the power efficiency. We report on the results of the simulations and compare these with our experimental results on substrate emitting microcavity LED's.

## II. Theoretical Model

We took a classical approach to calculate the spontaneous decay rate inside microcavities. It prescribes that the lifetime for spontaneous emission is inversely proportional to the spatially integrated radiation pattern of the decaying atom or recombining carriers [10], [11]. The set of recombining carriers can further be abstracted to a set of dipoles. The orientation of these dipoles depends on the particular material system involved.

As an example we consider the structure as shown in the inset of Fig. 1(a). The graph represents the light emission of a parallel-oriented dipole as a function of the angle $\theta$ within the cavity, with the active layer assumed to be transparent. This radiation pattern is the result of interference due to the multiple reflections at the mirrors on both sides of the active material [12]. The extraction efficiency to air is determined by the part of the radiation pattern within the semiconductor-air critical angle. The strong resonance perpendicular to the layer structure results in an increased extraction efficiency from the semiconductor to air. The radiation beyond the critical angle mainly consists of "leaky modes" escaping from the cavity to the substrate.

Next we allow the active material to be absorptive so that part of the light previously generated will be reabsorbed within the cavity. This active material is often a quantum-well (QW). The single pass absorption of QW's is very small, approximately 1%. However, because it sits exactly at the antinode of the standing wave pattern inside the microcavity, the absorption is greatly enhanced as it is the case with resonant detectors. Fig. 1(b) shows the radiation pattern in this case.

The decay rate involves the integration of the internal radiation pattern, including the strong resonance at an angle of 73°. At these large angles no power can be radiated to

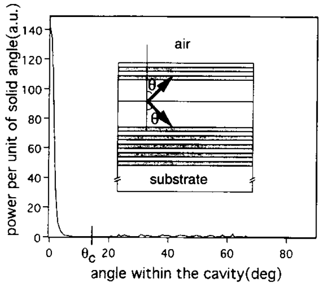
Manuscript received September 2, 1994; revised November 15, 1994. This work was supported by the IWT, Vlaams Instituut voor de bevordering van het Wetenschappelijk-Technologisch onderzoek in de industrie and from the European Community within the framework of ESPRIT B.R.A. Project Nr. 8447-SMILES, ESPRIT Working group Nr. 7070-PHOTONS, and by the Belgian IUAP-24 project.

H. De Neve is with the University of Gent—IMEC, Department of Information Technology, St. Pietersnieuwstraat 41, B-9000 Gent, Belgium and with IMEC MAP-MBE, Kapeldreef 75, B-3001 Leuven, Belgium.

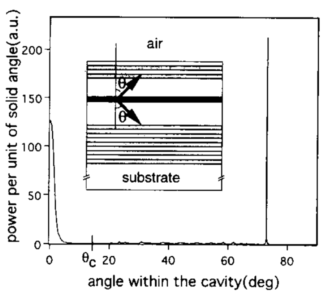
J. Blondelle, R. Baets, P. Demeester, and P. Van Daele are with the University of Gent—IMEC, Department of Information Technology, St. Pietersnieuwstraat 41, B-9000 Gent, Belgium.

G. Borghs is with IMEC MAP-MBE, Kapeldreef 75, B-3001 Leuven, Belgium.

IEEE Log Number 9408415.




(a)




(b)

Fig. 1. Light intensity as a function of angle inside the cavity for (a) lossless structure and (b) the same structure but with an absorbing QW. The GaAs $\lambda$-cavity is surrounded by two GaAs–AlAs DBR mirrors. $\theta_c$ indicates the GaAs-air critical angle. The strong resonance at larger angles corresponds to the guided mode of this structure.

the outside but because of the absorbing QW light is still generated and (re)absorbed inside the cavity by the QW. For each photon energy the light generation peaks at specific angles corresponding to the guided modes. If we lower the absorption factor of the active layer the peaks in the generated power of Fig. 1(b) approach a $\delta$-function. Due to discretisation the $\delta$-functions are not visible in Fig. 1(a). Thus the study of microcavities on the basis of the radiation pattern inside the cavity together with an absorbing active layer allows for an easy numerical calculation of the amount of light coupling to the guided modes. These modes strongly influence the extraction efficiency and the radiative decay rate enhancement.

The calculation of the absorbed optical power is nontrivial because optical source and absorber are at the same location. It can be done by comparing the amount of light which is generated by the QW to the power radiated to the outside.

The last part of the calculation consists of averaging the photon energy dependent decay rates and extraction efficiencies, thereby weighting with a Gaussian intrinsic spontaneous emission spectrum of given width.

## III. Design and Experimemtal Results

With the help of this simulation tool we optimized a substrate emitting microcavity LED. The InGaAs single QW is surrounded by a nonalloyed Ag mirror-contact (index of refraction = $0.2 - i\,6.5$) at the top reflecting 92% of the light and a GaAs–AlAs DBR mirror below. The QW was tuned to an emission wavelength of 980 nm. Earlier measurements

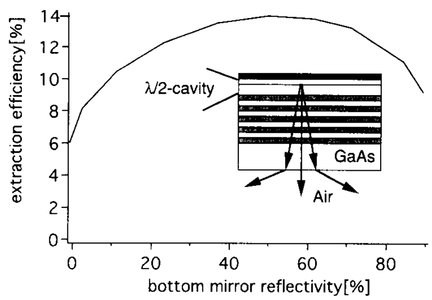



Fig. 2. Theoretical extraction efficiencies of the substrate emitting microcavity LED's under study as a function of the GaAs–AlAs DBR mirror reflectivity (number of layers).

indicate that the absorption of the 500 $\mu$m thick $n$-doped GaAs substrate at this wavelength is approximately 22%.

The overall quantum efficiency of these devices is the product of the internal quantum efficiency and the extraction efficiency. The values for the extraction efficiency refer to all the light emitted into air below the substrate, thus including all angles and all wavelengths, relative to the total amount of light generated inside the cavity. The intrinsic internal quantum efficiency is defined as the ratio of the radiative decay rate versus the total decay rate including all non-radiative decay mechanisms. For the simulation work we assumed it to be 90% in the absence of the microcavity. This value will be changed as the microcavity influences the radiative decay time. Furthermore we assumed an intrinsic QW emission spectrum with a FWHM = 40 nm, peaked at 980 nm. The simulations involve parallel oriented dipoles only because of the compressively strained InGaAs QW.

For comparison we first simulated a conventional substrate emitting LED with a QW sitting 500 nm below the Ag-contact and without DBR mirror, yielding an extraction efficiency of only 0.7%. Fig. 2 shows the evolution of the extraction efficiency for a $\lambda/2$ cavity as we increase the number of layers in the DBR mirror to increase the reflectivity. This calculation includes the reflection loss at the GaAs-air interface at the bottom of the wafer but does not account for the absorption in the substrate. The QW sits at the antinode of the standing wave pattern only 60 nm below the Ag mirror. The extraction efficiency peaks at a value of about 14% for a bottom reflectivity of 55%. Above 60% reflectivity the central part of the spectrum is more enhanced but the side parts are suppressed which causes a net decrease of the extraction efficiency. Once the reflectivity of the bottom mirror exceeds that of the Ag mirror, the absorption by the Ag and by the active layer lowers the extraction efficiency even further.

The simulations also revealed two important differences between $\lambda/2$ cavities and $\lambda$ cavities. First the radiative decay rate enhancement in a $\lambda/2$ cavity is a factor 1.25 higher with respect to a $\lambda$ cavity. This will induce a difference between the internal QE's of both cavities. Second the calculations indicate that in the $\lambda$ cavity roughly 30% of the light couples to the guided modes of the structure. If the guided modes are reabsorbed by the active layer this might give rise to an important photon recycling effect. These guided modes are suppressed in the $\lambda/2$ cavity.

TABLE I

THE OVERALL QE IS THE PRODUCT OF INTERNAL QE AND EXTRACTION EFFICIENCY. THE EXTRACTION EFFICIENCIES INCLUDE SUBSTRATE ABSORPITON (NOT THE CASE IN FIG. 2) AND REFLECTION LOSS AT THE BACK OF THE WAFER. A GOOD AGREEMENT BETWEEN EXPERIMENTAL AND THEORETICAL PREDICTED OVERALL QE IS FOUND FOR AN INTRINSIC INTERNAL QE (I.I.QE) OF 49%. THE VALUES FOR THE RADIATIVE DECAY RATE ENHANCEMENT ARE AVERAGED OVER ALL ENERGIES AND REFER TO AN InGaAs QW SITTING IN GaAs MATERIAL WITHOUT MIRRORS.

| | Extraction efficiency | | Theoretical overall QE (i.i.QE = 90%) | | Theoretical overall QE (i.i.QE = 49%) | | Experimental overall QE | | Central wavelength(nm) | | radiative decay rate enhancement | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | λ/2 | λ | λ/2 | λ | λ/2 | λ | λ/2 | λ | λ/2 | λ | λ/2 | λ |
| 6-DBR | 10.8% | 9.7% | 9.8% | 8.5% | 6.2% | 5.0% | 6.2% | 4.7% | 989 | 977 | 1.41 | 1.11 |
| 10-DBR | 9.2% | 7.1% | 8.6% | 6.3% | 5.4% | 3.6% | 5.5% | 3.9% | 992 | 974 | 1.43 | 1.10 |

To verify all these effects six different structures were grown. One part has a 6-period DBR mirror reflecting 65%, another set has a 10-period DBR reflecting 92%. On top of the mirror there is 66.3 nm $Al_{20}Ga_{80}As$ beneath the InGaAs QW which is surrounded by a 1.8 nm GaAs layer on each side. The top cladding consists of 30 nm $Al_{20}Ga_{80}As$ followed by 29 nm GaAs and a Ag mirror. Two regrowths of GaAs on the same samples provided an extra $\lambda/4$ and $\lambda/2$ layer before deposition of the Ag. More information about the growth conditions and the measurements can be found in [13]. The experimental results are summarised in Table I. The central wavelength measured in the direction normal to the layer structure is different for each cavity and was used to determine the exact layer structure. The theoretical quantum efficiencies in Table I refer to these structures. These values already take into account the substrate absorption measured to be 22% at these wavelengths. All devices exhibit a considerably better efficiency than conventional LED's, except for the off-resonance structure with the additional $\lambda/4$ layer and not described here. The best device exhibits an overall quantum efficiency of 6.2% measured at a current density of 100 A/cm$^2$. The quantum-well emission spectrum in the absence of a microcavity is centered around 977 nm. The cavity resonance in the direction normal to the surface is slightly detuned from this value and lies at 989 nm. By thinning the substrate and depositing an AR-coating we improved the quantum efficiency of this LED to 10.2%. The wall plug efficiency of this device is 10.5%. The output spectra were found to be insensitive to the current density and agreed well with theoretically predicted spectra. The narrowest spectrum was measured for the $\lambda$-cavity with the 10-period DBR and has a FWHM = 5.3 nm in the direction normal to the surface.

As seen in Table I, the experimental values of the quantum efficiency are about 60% of the theoretical predictions. A potential reason is the intrinsic internal QE, lower than the 90% which was originally assumed in the simulations [11]. We therefore fitted the experimental values to our model using the intrinsic internal QE as a fitting parameter with and without photon recycling. The latter could be important in the $\lambda$-cavity where roughly 30% of the light couples to the guided mode. The best fit was obtained at an intrinsic internal QE of 49% in the absence of any photon recycling. In the $\lambda/2$ cavities this value is significantly increased because of the radiative decay rate enhancements relative to the system without mirrors. These values are also presented in Table I. The impact of photon recycling at these low internal QE's is small. Higher internal QE's are needed to increase the overall QE and to estimate the importance of photon recycling for microcavity structures.

## IV. CONCLUSION

The analysis of guided modes, reabsorption of light and the photon recycling mechanism are incorporated in a simulation program for microcavities and proves useful in explaining the relative efficiencies of different substrate emitting microcavities. The very high power efficiencies in both theory and experiment prove the potential of microcavity LED's.

## REFERENCES


[1] D. G. Deppe, J. C. Campbell, R. Kuchibhotla, T. J. Rogers, and B. G. Streetman, "Vertically-coupled mirror-quantum well InGaAs-GaAs light emitting diode," *Electron. Lett.*, vol. 26, p. 1665, 1990.

[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] J. A. Lott, R. P. Schneider, Jr., J. C. Zolper, and K. J. Malloy, "AlGaInP visible resonant cavity light-emitting diodes," *IEEE Photon. Technol. Lett.*, vol. 5, pp. 631–633, 1993.

[4] U. Keller, G. R. Jacobovitz-Veselka, J. E. Cunningham, W. Y. Jan, B. Tell, and K. F. Brown-Goebeler, "Microcavity enhanced vertical-cavity light-emitting diodes," *Appl. Phys. Lett.*, vol. 62, pp. 3085–3087, 1993.

[5] N. E. J. Hunt, E. F. Schubert, R. A. Logan, and G. J. Zydzik, "Enhanced spectral power density and reduced linewidth at 1.3 mm in an InGaAsP quantum well resonant-cavity light-emitting diode," *Appl. Phys. Lett.*, vol. 61, pp. 2287–2289, 1992.

[6] E. F. Schubert, N. E. J. Hunt, M. Micovic, R. J. Malik, D. L. Sivco, A. Y. Cho, G. J. Zydzik, "Highly efficient light-emitting diodes with microcavities," *Science*, vol. 265, pp. 943–945, 1994.

[7] K. Ujihara, A. Nakamura, O. Manba, and Xiao-Ping Feng, "Spontaneous emission in a very short optical cavity with plane-parallel dielectric mirrors," *J. Appl. Phys.*, vol. 30, pp. 3388–3398, 1991.

[8] D. G. Deppe and C. Lei, "Spontaneous emission and optical gain in a Fabry–Perot microcavity," *Appl. Phys. Lett.*, vol. 60, pp. 527–529, 1992.

[9] S. T. Ho, S. L. McCall, and R. E. Slusher, "Spontaneous emission from excitons in thin dielectric layers," *Opt. Lett.*, vol. 18, pp. 909–911, 1993.

[10] W. Luckosz and R. E. Kunz, "Light emission by magnetic and electrical dipoles close to a plane interface. I. Total radiated power," *J. Opt. Soc. Am.*, vol. 67, no. 12, pp. 1607–1615, 1977.

[11] Z. Huang, C. C. Lin, and D. G. Deppe, "Spontaneous lifetime and quantum efficiency in light emitting diodes affected by a close metal mirror," *IEEE J. Quantum Electr.*, vol. 29, pp. 2940–2949, 1993.

[12] Z. Huang, C. Lei, D. G. Deppe, C. C. Lin, C. J. Pinzone, and R. D. Dupuis, "Spectral and intensity dependence on dipole localization in Fabry–Perot cavities," *Appl. Phys. Lett.*, vol. 61, pp. 2961–2963, 1992.

[13] J. Blondelle, H. De Neve, P. Demeester, P. Van Daele, G. Borghs, and R. Baets, "6% external quantum efficiency from InGaAs/(Al)GaAs single quantum well planar microcavity LED's," *Electron. Lett.*, vol. 30, p. 1787, 1994.