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C. Seassal, X. Letartre, J. Brault, M. Gendry, Patrick Pottier, et al.. InAs quantum wires in InP-based microdisks: Mode identification and continuous wave room temperature laser operation. *Journal of Applied Physics*, 2000, 88 (11), pp.6170-6174. 10.1063/1.1322381 . hal-02111579

HAL Id: hal-02111579

<https://hal.science/hal-02111579>

Submitted on 26 Apr 2019

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InAs quantum wires in InP-based microdisks: Mode identification and continuous wave room temperature laser operation

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(Received 5 June 2000; accepted for publication 11 September 2000)

We present the design, fabrication, and characterization of an optical microsource, which comprises InAs/InP quantum wires embedded in a suspended microdisk. Comparison between photoluminescence measurements and theoretical analysis allows for a clear identification of the whispering gallery modes. cw room temperature lasing operation is demonstrated. © 2000 American Institute of Physics. [S0021-8979(00)01024-0]

I. INTRODUCTION

Light generation, routing, and detection within a few microns distance, is getting more and more realistic thanks to the fast development of microdisks and photonic crystal-based micro/nanostructures. Light sources and filters using such structures have been demonstrated in several groups, paving the way to highly compact photonic integrated circuits. Notably, the performance of microdisk lasers have been considerably enhanced in just a few years: cw room temperature laser emission was recently obtained for a threshold current around 1 mA, with InP and GaAs-based heterostructure transferred onto a sapphire host substrate.¹ Moreover, Fujita *et al.* observed such a cw room temperature laser emission with a suspended InP-based heterostructure, with $I_{th} = 150 \mu A$.² Very recently, a $1.5 \mu m$ two-dimensional photonic crystal microlaser was demonstrated in the InGaAsP material system.³

On the other hand the use of quantum structures with a lower dimensionality than quantum wells, such as quantum dots (QDs), to realize low threshold lasers was proposed in 1982 by Arakawa and Sakai.⁴ It was predicted that, with a QD lateral size below $30 nm$ ⁵ and a reduced size distribution, it could be possible to decrease the threshold current of such lasers and to improve their temperature characteristics. These nanostructures can be grown self-organized by MBE, generally using the Stranski–Krastanow mode, that takes place due to the lattice mismatch between the QD material and the substrate. Lasers based on InAs QDs grown on GaAs have been fabricated and cw lasing has been achieved.⁵ However, higher uniformity and density are needed. Moreover, for optical communication, emitting wavelengths of 1.3 – $1.55 \mu m$ are requested.

By combining both low volume microcavities, such as microdisks, and low dimensionality quantum structures such as QDs or quantum wires (QWires), laser threshold can be drastically reduced. However, for such microsources, the constraints are quite stringent since the QDs and QWires should be densely packed, uniform in size, but also positioned where the electric field is the highest. The first two conditions are still not at hand, and the last one might not be achieved in the case of planar microcavities. Nevertheless, great advantage could be taken using “state of the art” low dimensional quantum structures since: (i) the nonradiative surface recombination is dramatically reduced since they are laterally encapsulated, (ii) the gain spectrum is much less affected by temperature, and (iii) population inversion is more easily achievable with such quantum structures.

For this purpose, InAs QDs and QWires on InP are attractive candidates that make possible the $1.3/1.5 \mu m$ emission wavelength achievable. It is useful to note that since encapsulated, the QDs/QWires are protected during sacrificial layer etching and it is possible to use InP barriers and InGaAs sacrificial layers together with InAs in the active region. This is an important aspect since the band offsets between InAs and InP are more important than in the more commonly used InGaAs/InGaAsP system. Nevertheless, this system is still not yet as optimized as the more classical InAs/GaAs system. For the InAs/InP nanostructures currently fabricated in our lab, density is higher, but their size must be reduced and its distribution sharpened.

In this article, we show the design, fabrication, and characterization of an optical microsource that integrates InAs QWires on InP, inside a suspended microdisk. We identify thoroughly the resonant cavity whispering gallery modes, by taking advantage of the wide emission spectrum of the QWires, consistent with their size distribution.⁶

In Sec. II, we describe in detail the design of the basic heterostructure and of the microdisk itself. Section III con-

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cerns the realization of the device. In Sec. IV, photoluminescence (PL) results are presented and discussed.

II. DESIGN

The basic system of the heterostructure is InAs/InP. We use the QWires presently achieved in our lab, i.e., with a PL spectrum centered at $1.7\ \mu\text{m}$. This is higher than the operational wavelength for optical communication, but this parameter should be controlled in the very near future. A single layer of QWires is realized in the middle of the InP barrier layer.

Then, one has to consider the microdisk configuration itself. In order to reduce the mode volume, the structure is mostly surrounded by air. For simplicity, we chose in a first instance the approach that consists of suspending the disk on a pedestal. We chose a $\lambda/(2n)$ optical thickness for the InP/InAs slab used for the microdisk, which behaves like a monomode waveguide with a maximum overlap and coupling between the guided field and the QWires layer. In addition, we chose a $3\lambda/4$ thickness for the air gap between the disk and the substrate, in order to minimize the coupling of the light generated in the QWires with the vertically radiated modes, which are radiation losses. We have already successfully used this effect elsewhere, for two dimensional (2D) photonic crystal cavities.⁷

To obtain a high Purcell factor F_P , one has to get an optical mode with the smallest volume V and the largest quality factor Q . In 1D Fabry-Pérot cavities, only a small F_P enhancement can be reached, as Q is nearly proportional to V . On the contrary, for 3D cavities like microdisks or photonic crystal cavities, strong F_P enhancements have been measured.^{8,9} Up to now, the best results were obtained on the GaAs microdisk in Ref. 8, with a F_P of 190. These authors showed that Q can be kept as high as 10 000, with a microdisk diameter as small as $2\ \mu\text{m}$. The modes of a disk are the so-called whispering gallery modes $\text{WGE}(H)_{mln}$, where m , l , and n are integers relative to azimuthal, radial, and vertical field distributions. It is assumed that the QWires have a width to thickness ratio high enough to consider that only WGE modes are generated (in-plane polarization of the E field). In our case, the disk is monomode along the vertical direction and $n=0$. It must be pointed out that, when the microdisk lies on a pedestal, the field associated with these high Q modes is strongly localized at the periphery of the disk. We can thus predict that only modes with very low l (0 or 1) will be observed. Finally, the $3.85\ \mu\text{m}$ disk diameter is chosen in such a way that the effective free spectral range (FSR) between the effective optical resonance modes is about a few tens of nanometers, as this is usually required in wavelength division multiplexing communication systems. A schematic cross-section view of the device is shown in Fig. 1(a).

III. FABRICATION

The samples were grown by solid-source molecular beam epitaxy (using As and P valved cracking cells) on semi-insulating InP(001) substrates in a Riber reactor. The lattice matched InGaAs sacrificial layer was grown at

FIG. 1. Schematic cross-section view (a) and SEM micrograph (b) of the microdisk.

480°C . Then, the temperature was decreased to 450°C for the growth of the InP and the InAs layers. A $1.6\ \text{nm}$ InAs strained layer was grown at a $\sim 0.88\ \mu\text{m/h}$ growth rate and with an As_2 pressure of 4×10^{-6} Torr. Then, the surface was maintained 20 s under As_2 pressure which allowed a 2D/3D growth transition and thus the formation of InAs quantum wires.

Cross-section and plan view TEM micrographs realized on this structure, are presented in Fig. 2. Figure 2(b) shows that, wire-like nanostructures aligned along $[1\bar{1}0]$ are developed. These QWires are $2.5\text{--}3\ \text{nm}$ high, $25\ \text{nm}$ wide, $100\text{--}200\ \text{nm}$ long, and their density is about $4.5 \times 10^5\ \text{cm}^{-1}$.

$3.85\ \mu\text{m}$ diam microdisks are then patterned by electron beam lithography on poly(methylmethacrylate). The patterns are transferred to a $175\ \text{nm}$ thick PECVD deposited SiO_2 mask, using CHF_3 reactive ion etching (RIE), and then to the heterostructure, also by RIE, with a gas mixture of 15 sccm CH_4 , 30 sccm H_2 , and $0.9\ \text{sccm}$ O_2 , at a pressure reduced to 30 mTorr, with a 200 W rf power. With this simple dry etching technique, very smooth and almost vertical sidewalls can be processed. The InGaAs sacrificial layer is under-etched using a $\text{HF}:\text{H}_2\text{O}_2:\text{H}_2\text{O}$ (1:1:10) solution, which is completely selective with regard to InP. A small InGaAs pedestal, with a minimum submicronic diameter, is left to maintain the microdisk [see Fig. 1(b)].

FIG. 2. Cross-section TEM view along the $[1\bar{1}0]$ direction (a) and top TEM view along the $[001]$ axis (b). The InAs nanostructures appear in black and InP in white.

IV. RESULTS AND DISCUSSION

The devices are analyzed by spectral PL. An AlGaAs laser diode, emitting a cw signal around 800 nm is used for optical pumping. Using a $\times 50$ objective lens (0.7 numerical aperture), the laser beam is focused on the surface of the sample, with a $1\ \mu\text{m}$ spot size. The PL signal is partly coupled to the cavity modes (the whispering gallery modes of the disk), which experience diffusion phenomena on the edge of the structure. This results in optical losses, which control partly the Q factor, and are detected and analyzed, using the same objective lens. Another part of the PL signal is coupled to modes that are directly vertically radiated. But, as mentioned in Sec. II, this part is significantly inhibited by carefully choosing the optical thicknesses and the position of the QWires layer. Therefore, PL spectral characteristics depend both on the QWire properties and on the cavity shape and dimensions.

For a pumping level of 1 mW, spontaneous emission occurs, and seven optical modes clearly appear on the PL spectrum, over a 250 nm spectral range (Fig. 3). The measured Q factor of the cavity modes reach values ranging from

FIG. 3. PL spectrum of the microdisk, with a pumping level of 1 mW. The spectral resolution is around 2 nm.

300 to 1000, which corresponds to the maximum resolution of our spectrometer.

In order to identify the measured resonant modes, an approximate calculation was first made, based on the method described in Ref. 10, where the vertical distribution of the electromagnetic field is accounted for by an effective index. Then, a rigorous finite element analysis is performed to validate the obtained resonance frequencies. This method can be used to perform electromagnetic simulations for 2D or 3D structures in free or forced oscillations, with or without dielectric and metallic losses of the materials. The mesh's elements for the FEM calculation are described by Nedelec's polynoms. In this application, to determine resonant frequencies and the electromagnetic field of whispering gallery modes, a 2D formulation is sufficient by using cylindrical symmetry. So, only a half resonator's transversal cut is analyzed. Calculations are performed assuming that the reabsorption is negligible, that the material is nondispersive, and considering that the influence of the pedestal is negligible. The presence of two kinds of modes is predicted: WGE_{ml0} , with $l=0$ and 1. Corresponding typical field distributions for such modes are displayed in Fig. 4. Theoretical values of the mode wavelength are presented in Fig. 5, together with the experimental values extracted from the PL spectra. They split into two categories, corresponding to two ranges of Q factors of the modes, namely 300–500 and 800–1000. The experimental mode wavelengths are particularly close to the values predicted by both theoretical methods. Even the simple and fast “effective index” method leads to an accuracy better than 1%. For the lower order radial distribution ($l=0$), experimental mode wavelengths are in excellent agreement with the prediction made by the exact finite element analysis. For the higher order radial distribution, $l=1$, the agreement is not as good and also the Q factor is lower. The Q dependence of the modes is well explained, considering that the low- Q modes ($l=1$) extend over a wider surface, including the area of the pedestal. This also affects significantly the effective index of such modes, and results in a redshift of their resonance wavelength, as compared to the mode wavelengths calculated for the ideal microdisk. Loss induced by the pedestal inhibits high- l modes, which results in a wider experimental FSR. For laser operation, in particu-

FIG. 4. Field distribution of the $WGE_{14,0,0}$ (a) and $WGE_{14,1,0}$ (b) modes calculated by the FEM method.

lar, this makes wavelength selection easier. The complete mode identification, indicated in Fig. 5, is straightforward due to the very close relation between calculated and experimental data.

FIG. 5. Experimental mode wavelength compared with values calculated by WKB and with the EMXD software (dedicated to 2D and 3D FEM analysis).

FIG. 6. PL spectrum of the microdisk at 3 mW, i.e., over the threshold.

Other PL measurements were performed at higher pumping power. From 2 mW, stimulated emission occurs. Only one high- Q optical mode, standing at 1683 nm, is selected within the gain spectrum of the QWires (Fig. 6), and for higher power levels the corresponding light power increases linearly (see Fig. 7). This laser emission was observed at room temperature, and by pumping the structure continuously. This laser emission was observed in planar microcavity structures with a quantum structure of lower dimensionality than quantum wells. Mainly because of the wide distribution of the QWires, but also because heat sinking is reduced by the topology of the structure, the threshold power could not be reduced below 1 mW. In our sample, a single QWire layer was used, with a wide size distribution. Then, only a few QWires interact with the laser mode, which leads to a very small optical gain.⁸ This indicates that these microdisks are very high Q cavities.

V. CONCLUSION

We designed, fabricated, and tested a microdisk microcavity structure operating around $1.7 \mu\text{m}$, with InAs QWires in the active zone. The observed spontaneous emission spectrum is very close to predictions and the optical modes, probed on a wide spectral range, are completely identified. By using this InAs/InP material system, and by encapsulating the quantum structures, the surface recombination effects are dramatically reduced, and do not affect the device properties. Finally, cw laser operation was achieved at room temperature.

FIG. 7. PL intensity vs optical pumping level at 1683 nm. The laser emission occurs above 2 mW.

Optimization of the InAs/InP quantum structures is underway in our group. InAs QDs are now at hand; further improvement aims at sharpening the size distribution of these nanostructures.

ACKNOWLEDGMENTS

The authors wish to acknowledge M.-P. Besland for SiO₂ deposition and M. Garrigues for his kind experimental support. This work was supported by the CNRS “microsystems” program.

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