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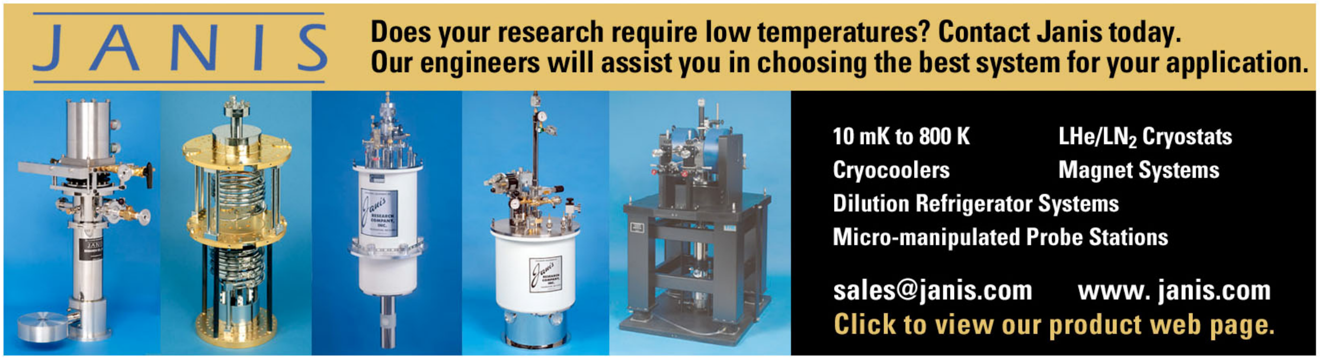

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All-dielectric GaN microcavity: Strong coupling and lasing at room temperature

K. S. Daskalakis,[1,2,a)] P. S. Eldridge,[3] G. Christmann,[4] E. Trichas,[1,3] R. Murray,[2]
E. Iliopoulos,[3,5] E. Monroy,[6] N. T. Pelekanos,[1,3] J. J. Baumberg,[4] and P. G. Savvidis[1,3]
[1]*Department of Materials Science & Technology, University of Crete, 71003 Crete, Greece*
[2]*The Blackett Laboratory, Imperial College London, Prince Consort Road, SW7 2AZ, London, United Kingdom*
[3]*Microelectronics Research Group, FORTH/IESL, P.O. Box 1385, 71110 Heraklion, Greece*
[4]*NanoPhotonics Centre, Cavendish Laboratory, University of Cambridge, J. J. Thomson Avenue, Cambridge CB3 0HE, United Kingdom*
[5]*Department of Physics, University of Crete, P.O. Box 2208, 71003 Heraklion, Greece*
[6]*CEA/CNRS Group Nanophysique et semiconducteurs, INAC/SP2M/NPSC, CEA-Grenoble, 17 rue des Martyrs, 38054 Grenoble Cedex 9, France*

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The strong light-matter coupling regime and lasing in a GaN microcavity fabricated by incorporating a high optical quality GaN membrane inside an all-dielectric mirror cavity is demonstrated at room temperature. A nonlinear increase of the emission and line narrowing marks the onset of polariton lasing regime with significantly reduced threshold compared with previous reports for bulk GaN microcavity. This combination of low lasing thresholds and ease of fabrication allows incorporation of quantum wells and electrical contacts into the active region, paving the way for electrically driven room temperature (RT) polariton laser devices. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4795019]

Two decades on from the first demonstration of strong light-matter coupling in a semiconductor microcavity, the realization of an electrically pumped polariton laser—the holy grail in microcavity—research remains elusive.[1,2] As electrical injection into ZnO and organic based microcavities is technologically challenging, GaN based microcavities operating in the strong coupling regime are currently considered as the most promising candidates for implementation of such robust, ultra-low threshold, room temperature polaritonic laser devices.[3–7] Several crucial factors, namely, the requirement for high finesse optical cavities and uniform pumping in the active region of GaN microcavities have yet to be fully addressed.[8]

The former drastically reduces the lasing threshold of polariton lasers,[9] whilst the latter, as recent optical pulsed and quasi-CW pumping experiments show,[10,11] is necessary to obtain the relatively high carrier densities required for lasing, particularly in an electrically pumped device. Although monolithic fabrication of GaN microcavities offers many advantages, it does not provide the necessary flexibility in fabrication and leads to restrictively narrow reflectivity stopbands that become comparable with the large Rabi-splitting.

In this work, we develop an alternative route, utilizing selective photo-electro-chemical (PEC) etching[12] of an InGaN sacrificial layer, to produce high optical quality GaN membranes.[13–16] Such membranes are integrated into an all-dielectric microcavity, to demonstrate the strong coupling regime and low threshold lasing at room temperature under non-resonant optical excitation. The ease of fabrication offers several advantages. It allows achievement of high finesse optical cavities using broadband dielectric mirrors. Furthermore, electrical contacts can now be deposited on the membrane itself, allowing electrical injection directly in the active region of the microcavity device.[8]

The GaN sample, fabricated by plasma-assisted molecular beam epitaxy (PA-MBE), consists of a 50 nm $In_{0.1}Ga_{0.9}N$ sacrificial layer followed by a c-plane 210 nm GaN film deposited on commercial 3 μm thick unintentionally doped (0001)-oriented GaN buffer layer on sapphire templates. A standard lithographic process is applied to evaporate a 40 μm × 40 μm grid of the top dielectric DBR mirrors (10 repeats of SiO_2/Ta_2O_5), which serve as a hard mask to define rectangular 1 μm high mesas by reactive ion etching (RIE). The exposed sacrificial layer of $In_{0.1}Ga_{0.9}N$ is PEC etched by a KOH-concentration-optimized solution, with the result illustrated in Fig. 1(a).[14] The sample is then flipped for the evaporation of the second dielectric DBR mirror[13] forming a $3\lambda/2$ microcavity sample shown in Fig. 1(d). The particular choice of cavity thickness was chosen to balance the need for mechanical stability of the etched membrane and minimal cavity mode volume.

The microsized all-dielectric GaN microcavities are initially characterized using an angular resolved white light (WL) μ-reflectivity set-up shown in Fig. 1(d), which allows simultaneous imaging of the sample's surface. The light from a Xenon lamp is focused down to a 10 μm diameter spot using a microscope objective (numerical aperture = 0.546) used for both excitation and real space imaging. The reflected/emitted light is collected through an UV grade 400 μm fiber coupled to a CCD spectrometer. Access to energies above 3.59 eV is restricted because these energies fall within the absorption band of the microscope objective.

Microcavity dispersion relations are measured by producing an image plot of the angle dependent reflectivity

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[a)] Electronic mail: k.daskalakis11@imperial.ac.uk.

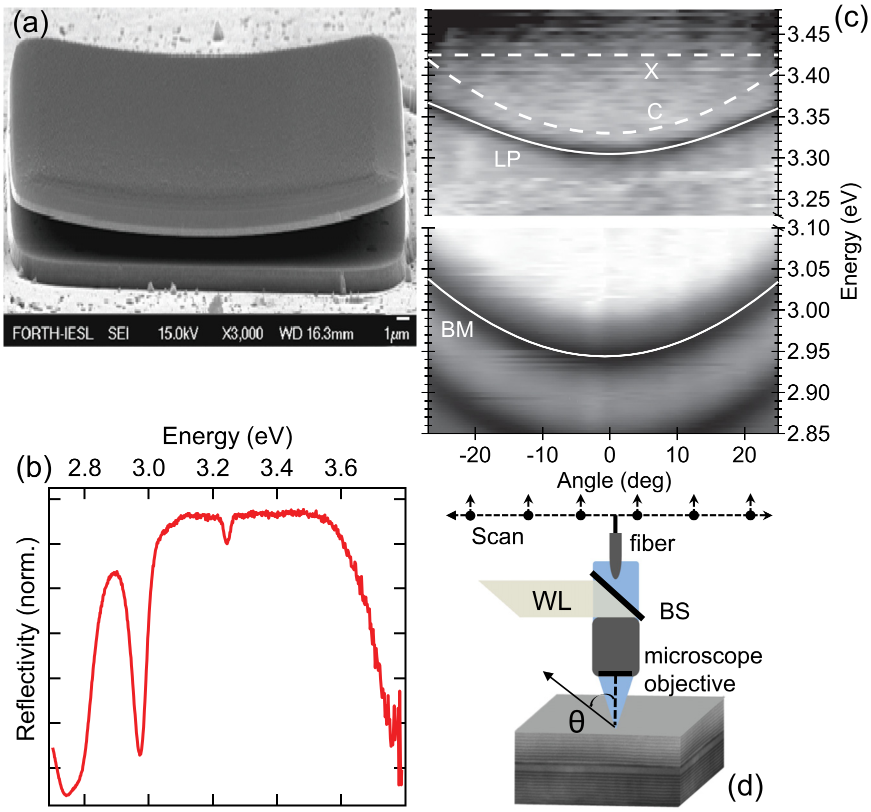

FIG. 1. (a) SEM image of a free standing GaN membrane with dielectric DBR used as etch mask. (b) μ-reflectivity spectra of a complete structure measured at normal incidence. (c) Image plot of the angle resolved μ-reflectivity spectra. The dashed lines X, C correspond to exciton and cavity mode dispersions, whereas LP and BM branches marked by solid lines are modelled lower polariton and Bragg modes, respectively. (d) Schematic of the angle resolved μ-reflectivity setup and SEM cross-section of the microcavity sample.

spectra in Fig. 1(b), acquired by scanning the fiber position behind the objective. Figure 1(c) shows the resulting contour plot and the extracted reflectivity dip positions marked by the solid white line taken at negative detuning of ($\delta = -95$ meV). The data confirm that the sample has a well defined cavity mode and a wide reflectivity stopband. Furthermore, the lower polariton (LP) branch exhibits reduced curvature at higher angles compared with low energy Bragg mode dispersion (shown below on the same scale), indicating the onset of the strong coupling regime. Although the numerical aperture of the objective allows access to a wide range of angles approaching 30°, this measured range is insufficient for unambiguous identification of the strong coupling regime via μ-reflectivity measurements. Unambiguous proof of the strong coupling regime comes from angle-resolved μ-photoluminescence (PL) measurements which allow access to a larger angular range.

Figure 2 shows image plots of angle resolved PL emission for two membranes with different thicknesses, corresponding to exciton cavity-mode detunings of -55 meV (left) and -45 meV (right) under non-resonant optical pumping at 325 nm by a He-Cd laser. For both detunings, clear anticrossing behaviour is observed for the lower branch which, at large angles, converges to the exciton energy of 3.41 eV. Contrarily, the low energy Bragg modes are found to be continuously dispersive up to very large angles in good agreement with transfer matrix simulations for the specific dielectric materials. A similar result is obtained for the bare cavity mode shown by the dashed line. The above observations are clear manifestation of the presence of the strong light-matter coupling regime. Notably, as in most bulk active region microcavity cases, emission from the upper polariton branch cannot be easily resolved, because of the absorption by the continuum of electron hole states which are not sufficiently separated from the exciton energy. Despite this, a coupled harmonic oscillator model yields a good measure of the Rabi-splitting in this system which is estimated to be 55 meV (Fig. 2). The good quality of the sample is independently confirmed by higher resolution and optimally focussed normal incidence μ-PL measurements yielding a cavity quality factor of 600.

We examine the nonlinear and lasing properties of this hybrid all-dielectric microcavity by exciting the sample at a

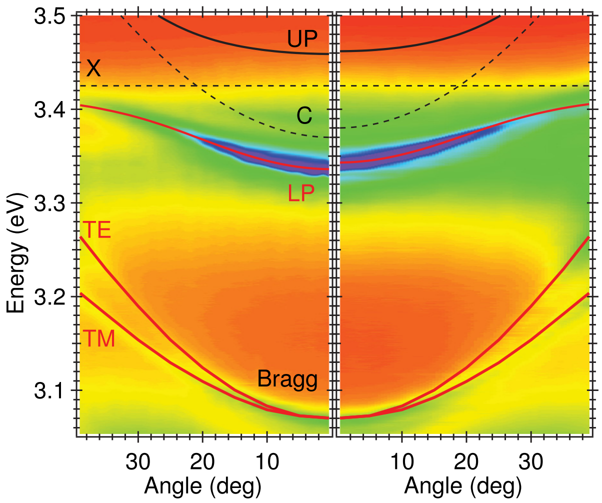

FIG. 2. Image plots of the RT μ-PL showing strong coupling regime for two different detunings (left, right). The dashed lines X, C show the exciton and cavity mode dispersions, whereas the solid lines labelled LP and UP correspond to the calculated lower and upper polariton branches from a two coupled oscillator model. The solid lines labelled TM and TE correspond to the polarization split Bragg modes.

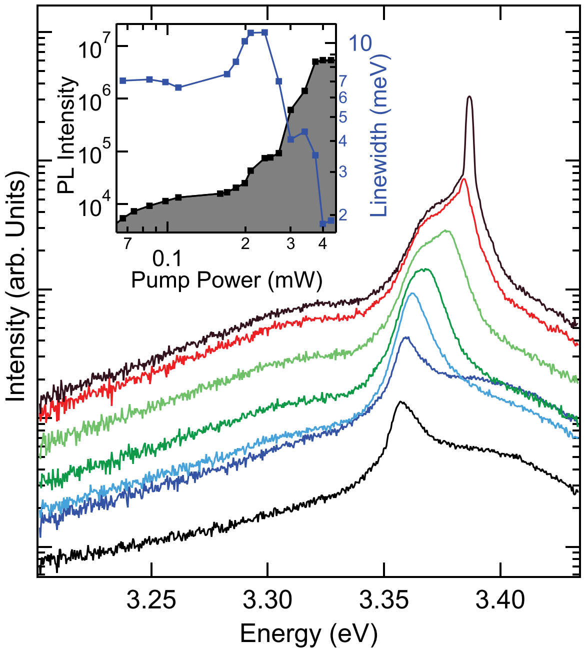

FIG. 3. Power dependent PL spectra showing nonlinear increase and blueshifted emission accompanied by reduction in the emission linewidth (inset) above threshold of 180 μW.

45° incidence angle with a pulsed 0.51 ns frequency-quadrupled Nd-Yag laser at 266 nm and 7.58 kHz repetition rate. Power dependent emission spectra obtained at normal incidence are recorded in Fig. 3. The nonlinear increase in the PL above the threshold of 180 μW is blueshifted with respect to the low power emission accompanied by a simultaneous reduction in the linewidth as clearly seen in the inset of Fig. 3. Direct comparison of the lasing threshold between previously reported short pulse excitation[10] and our quasi-CW excitation experiment is not straight-forward. However, a simple evaluation of peak power densities derived by normalizing average recorded powers by the duty cycle of the laser pulse suggests a significant threshold reduction compared with previous reports for bulk GaN system.[10] We attribute this lowering of the threshold to the high finesse and good optical quality of the GaN microcavity operating in the strong coupling regime.

In conclusion, by performing μ-reflectivity and μ-PL measurements, we report observation of the strong coupling regime and lasing at room temperature in GaN microcavities fabricated by incorporation of high quality GaN membranes inside an all-dielectric cavity. These next generation bulk GaN samples exhibit reduced lasing thresholds whilst ease of their fabrication allows incorporation of quantum[17,18] wells and electrical contacts into the active region.

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