# Room-temperature polariton lasers based on GaN microcavities

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The critical temperature for Bose condensation of exciton polaritons in an AlGaN microcavity containing 9 GaN quantum wells is calculated to be $T=460$ K. We have modeled the kinetics of polaritons in such a microcavity device using the two-dimensional Boltzmann equation. Room-temperature lasing is found with a threshold as small as 100 mW. The kinetic blocking of polariton relaxation that prevents formation of the Bose-condensed phase of polaritons at low temperatures disappears at high temperatures, especially in *n*-doped samples. Thus, GaN microcavities are excellent candidates for realization of room-temperature polariton lasers. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1494126]

In recent years planar semiconductor microcavities (MCs) have attracted a lot of attention due to the possibility of enhancing and controlling the interaction between light and electronic excitations in these structures. If the coupling between the exciton and the photon mode of the resonators is strong enough, this has been shown to result in a pronounced Rabi splitting in the two-dimensional (2D) cavity spectra.[1] This observation has generated much speculation regarding the possibility of low-threshold optical devices[2] based on Bose condensation of exciton polaritons.[3] In contrast with the polaritons in bulk crystals, MC polaritons have a quasi 2D nature, with a finite energy at zero wave vector $k=0$. They are also characterized by an in-plane effective mass four orders of magnitude smaller than that of quantum well (QW) excitons. These properties allow the study of bosonic effects in MCs that cannot be achieved in bulk semiconductors or in a pure excitonic system.[4,5] This paves the way towards the realization of so-called "polariton lasers" in which the thermalized distribution of polariton quasiparticles spontaneously collapses into one state only. A feature of these devices is that no population inversion is required to achieve optical amplification in such a system: it arises as soon as the relaxation of excitations into the ground state exceeds their escape time.

However, experimental observation of this effect is prevented at low temperature in conventional GaAs- or II–VI-based microcavities because of the slow rate of relaxation of photoexcited polaritons down to the bottom of the lower polariton (LP) band.[6–9] Moreover, the strong exciton-light coupling regime necessary for polariton lasing does not hold at room temperature in these structures because the thermal broadening of the exciton resonance exceeds its binding energy. Thus for realization of practical polariton laser devices, a different material is needed which allows fast polariton relaxation together with temperature-resistant excitons.

Here, we present a realistic model room-temperature polariton laser based on a GaN microcavity. GaN fits three major material's requirements neccessary for observing polariton lasing:

(1) GaN excitons are stable at room temperature;
(2) the light-matter coupling is enormously strong, as we will show below; and
(3) GaN technology is now increasingly well developed, and the observation of the strong coupling regime in such structures seems likely to be achieved.

Our model microcavity consisted of 9 GaN quantum wells (QWs) of 4 ML width each embedded inside the 3 $\lambda/2$ $Al_{0.1}Ga_{0.9}N$ microcavity [Fig. 1(a)]. The cavity is sandwiched between $Al_{0.2}Ga_{0.8}N/Al_{0.9}Ga_{0.1}N$ Bragg mirrors having 11 pairs of $\lambda/4$ layers (upper mirror) and 14 pairs of $\lambda/4$ layers (bottom mirror). The structure is intended to be grown on a GaN substrate. An alternative possibility is to grow an oxide dielectric mirror on the top of the sample.[10] The 4 monolayer thick QWs are grouped in threes at each antinode of the electric field of the microcavity eigenmode. All the parameters we use in the calculation are those of existing structures. Namely, the QW exciton energy (3543 meV), oscillator strength (0.6 meV), and inhomogeneous broadening

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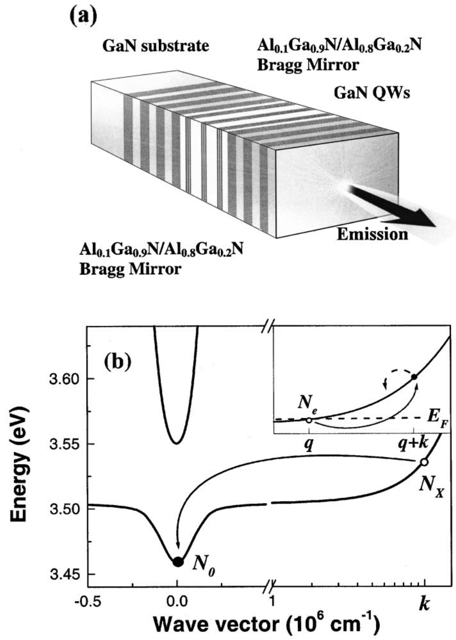


FIG. 1. (a) Schematic of the proposed microcavity structure. (b) Calculated upper and lower (LP) dispersion of exciton polaritons in this cavity at zero detuning between photon and exciton modes. The arrow shows schematically the resonant relaxation of polaritons of the reservoir ($N_x$) to their ground state ($N_0$) via their scattering with a free electron coming from the Fermi level ($N_e$). The electron cooling is ensured via their interaction with acoustic phonons (dashed arrow of the inset).

(8 meV) are taken from Ref. 11. A single exciton resonance is considered. The refractive indices of AlGaN are taken from Ref. 12. The polariton dispersion relation of the microcavity for small wave vectors and for zero detuning between the exciton and the cavity mode is obtained by the scattering state method[13] [Figure 1(b)]. A remarkable fact is that the vacuum-field Rabi splitting between upper and lower polaritons exceeds 90 meV in our system. Thus, *the strong coupling in GaN microcavities is convincingly retained at room temperature* which is one of the most important conditions for realization of room-temperature polariton lasers.

The Bose condensation is expected to appear as a result of polariton relaxation at the bottom of the LP branch (into the $k=0$ state). In order to accelerate this relaxation we assume that a small concentration of free electrons is introduced into the cavity.[14] Figure 2 shows the critical density of formation of the condensed phase for the polaritons in the cavity (solid line). In a model of an ideal Bose gas it is given by

$$n_c(T)=\frac{1}{(2\pi)^2}\int_{\mathbf{k},k\geqslant 2\pi/R} N_{\mathbf{k}}(\mu=0)d\mathbf{k}, \tag{1}$$

where

$$N_{\mathbf{k}}=\frac{1}{\exp\left[\dfrac{E(\mathbf{k})-E(0)-\mu}{k_bT}\right]-1}, \tag{2}$$

$E(\mathbf{k})$ is the exciton-polariton energy as a function of its wave-vector $\mathbf{k}$, taken from Fig. 1(b),[15] $\mu$ is the chemical potential, $k_b$ is the Boltzmann constant, $T$ is the temperature, and $R$ is the radius of the excitation spot which is optically or electrically pumped, and assumed to be 50 $\mu$m.

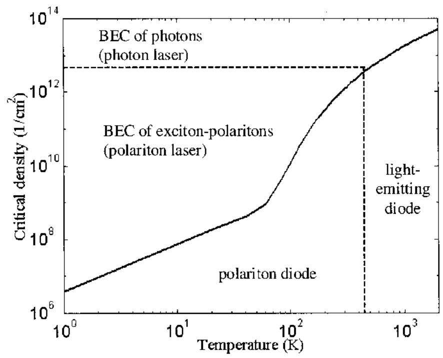


FIG. 2. Exciton-polariton phase diagram in the GaN microcavity. Solid line shows the polariton critical density as a function of the lattice temperature. The vertical dashed line shows the exciton thermal dissociation limit. The horizontal dashed line shows the Mott transition for excitons.

Vertical and horizontal dashed lines in Fig. 2 show the limits of stability of the exciton polaritons that are imposed by exciton screening from the photoinduced electron-hole plasma (horizontal line) or from the temperature-induced broadening of the exciton resonance (vertical line). Note that in our structure the exciton-polariton screening occurs at an optical pumping density nine times larger than for a single QW[16] due to the presence of nine QWs embedded within the cavity. One can see that the Bose condensation of polaritons is possible for a large range of temperatures and pumping powers limited by a critical temperature $T_{\mathrm{C}}$ proportional to the exciton binding.

In our case $T_{\mathrm{C}}=460$ K. In contrast, we note that the critical temperature for the Bose condensation of Wannier–Mott excitons is only of the order of hundreds of mK[5] and that the critical temperature of polariton lasing in conventional GaAs cavities estimated in the same way is lower than 100 K for the best samples available. The proposed system thus offers a chance to observe Bose condensation of massive quasiparticles in solids at temperatures at and above room temperature.

Below the critical density, the microcavity device operates in the regime of a polariton diode in the strong coupling regime, while in the weak coupling regime the device behaves like a conventional light-emitting diode (Fig. 2). Above the critical density, in the weak coupling regime, the microcavity acts as a conventional laser.

However, it should be noted that additional *kinetic* conditions are imposed on the critical parameters of the polariton Bose condensation in MCs. Below the critical temperature and carrier density, exciton-polariton Bose condensation takes place if the polariton relaxation to the $k=0$ state is fast enough with respect to their radiative decay rate. In order to examine the polariton kinetics we have solved numerically the 2D Boltzmann equation that describes our system

$$\frac{dn_{\mathbf{k}}}{dt}=P_{\mathbf{k}}-\Gamma_{\mathbf{k}}n_{\mathbf{k}}-n_{\mathbf{k}}\sum_{\mathbf{k}'} W_{\mathbf{k}\to\mathbf{k}'}(n_{\mathbf{k}'}+1)$$
$$+(n_{\mathbf{k}}+1)\sum_{\mathbf{k}'} W_{\mathbf{k}'\to\mathbf{k}}n_{\mathbf{k}'}, \tag{3}$$

where $n_{\mathbf{k}}$ is the polariton distribution function which is assumed to have a cylindrical symmetry, $P_{\mathbf{k}}$ is the generation term, $\Gamma_{\mathbf{k}}$ describes the escape of polaritons via radiative and

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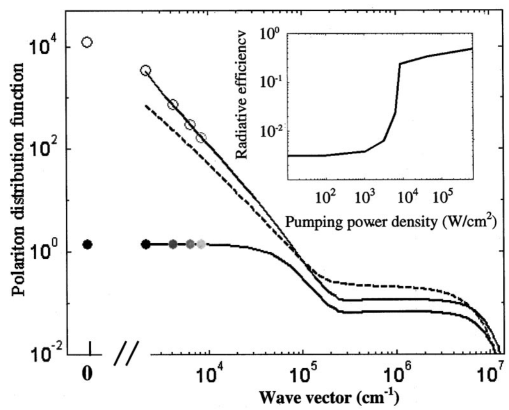


FIG. 3. Solid lines: exciton-polariton kinetic distribution functions of the GaN microcavity under nonresonant cw optical pumping at 300 K. The pump power densities used are (a) 1000 W/cm$^2$ and (b) 40 000 W/cm$^2$. Black points and open circles show the values of the distribution function for the lowest energy states (assuming the exciting light spot is 50 $\mu$m radius) for pump densities of 1000 W/cm$^2$ and 40 000 W/cm$^2$, respectively. Dashed line shows the Bose–Einstein polariton distribution function of the same microcavity assuming a vanishing chemical potential. Inset shows the radiative efficiency of the polariton laser vs the pumping power density at 300 K.

nonradiative recombination channels. We calculate $\Gamma_{\mathbf{k}}$ as in Ref. 6 using the cavity photon lifetime of 130 fs and the exciton nonradiative decay time of 100 ps. $W_{\mathbf{k}' \to \mathbf{k}}$ is the rate of polariton scattering between the states characterized by the wave vectors $\mathbf{k}$ and $\mathbf{k}'$. In our model it is composed of three terms that describe the polariton-acoustic phonon scattering,[6] the polariton–polariton scattering,[6] and the polariton-electron scattering.[14] We do not consider the piezoelectric scattering since it is negligible at room temperature.[17]

We assume an electron mass of 0.2$m_e$ and an electron density of $10^{11}$ cm$^{-2}$, well below the exciton bleaching limit.[16] Because of their small mass and of their strong Coulomb interaction with the excitons, electrons provide efficient scattering of the polaritons towards their ground state. Note also that the strong electron–electron interactions and the fast electronic thermal diffusion in the plane of the QWs lead to fast cooling of the electron gas back down to the lattice temperature within the excitation area. The energy of hot polaritons within this excitation area is transferred to the electronic reservoir of the entire sample and then slowly transferred to the crystal lattice via electron-phonon interactions.

Figure 3 shows the equilibrium distribution functions of the exciton polaritons in our cavity at the continuous wave (cw) nonresonant excitation density of (a) 1000 W/cm$^2$ or (b) 40 000 W/cm$^2$. The discrete nature of the reciprocal space is taken into account for the lowest energy states corresponding to $k=0$, $k=2\pi/R,\ldots$ . At the small excitation density (a) the population of the polariton ground state $n_0$ is approximately unity, marking the threshold to the bosonic amplification regime. For a large excitation density (b), $n_0 \approx 10^4$. In this case the Bose condensation of the MC polaritons is definitely achieved, as one concludes when comparing the curve (b) with the Bose–Einstein distribution function of the exciton polaritons calculated according to Eq. (2) for $\mu=0$ (dashed line). The radiative efficiency of the laser[18] versus pumping power is presented in the inset. It shows a clear threshold amplification at the extremely low power of 100 mW and a quantum efficiency close to 50%. Smaller area devices have a correspondingly smaller threshold power, so we envisage thresholds below 1 mW.

In conclusion, we have shown that a new generation of optoelectronic devices called polariton lasers, based on the Bose condensation of MC polaritons, can be realized with the use of $n$-doped microcavities based on GaN materials. The model polariton laser we have considered here is based on current technologies and shows an extremely low threshold power at room temperature and a high quantum efficiency.

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[1] C. Weisbuch, M. Nishioka, A. Ishikawa, and Y. Arakawa, Phys. Rev. Lett. **69**, 3314 (1992).
[2] P. G. Savvidis, J. J. Baumberg, R. M. Stevenson, M. Skolnick, D. M. Whittaker, and J. S. Roberts, Phys. Rev. Lett. **84**, 1547 (2000); J. J. Baumberg, P. G. Savvidis, R. M. Stevenson, A. I. Tartakovskii, M. S. Skolnick, D. M. Whittaker, and J. S. Roberts, Phys. Rev. B **62**, R16247 (2000).
[3] Polaritons being mixed as exciton-photon quasiparticles, see, e.g., L. C. Andreani, in *Confined Electrons and Photons*, edited by E. Burstein and C. Weisbuch (Plenum, New York, 1995), p. 57.
[4] L. Keldysh and A. N. Kozlov, Zh. Eksp. Teor. Fiz. **54**, 978 (1968) [Sov. Phys. JETP **27**, 521 (1968)].
[5] L. V. Butov, A. L. Ivanov, A. Imamoglu, P. B. Littlewood, A. A. Shashkin, V. T. Dolgopolov, K. L. Campman, and A. C. Gossard, Phys. Rev. Lett. **86**, 5608 (2001).
[6] F. Tassone, C. Piermarocchi, V. Savona, A. Quattropani, and P. Schwendimann, Phys. Rev. B **56**, 7554 (1997).
[7] A. I. Tartakovskii, M. Emam-Ismai, R. M. Stevenson, M. S. Skolnick, V. N. Astratov, D. M. Whittaker, J. J. Baumberg, and J. S. Roberts, Phys. Rev. B **62**, R2283 (2000).
[8] P. Senellart, J. Bloch, B. Sermage, and J. Y. Marzin, Phys. Rev. B **62**, R16263 (2000).
[9] L. S. Dang, D. Heger, R. Andre, F. Boeuf, and A. Romestain, Phys. Rev. Lett. **81**, 3920 (1998).
[10] M. Diagne, Y. He, H. Zhou, E. Makarona, A. V. Nurmikko, J. Han, K. E. Waldrip, J. J. Figiel, T. Takeuchi, and M. Krames, Appl. Phys. Lett. **79**, 3720 (2001).
[11] M. Zamfirescu, B. Gil, N. Grandjean, G. Malpuech, A. Kavokin, P. Bigenwald, and J. Massies, Phys. Rev. B **64**, 12130(R) (2001).
[12] D. Brunner, H Angerer, E. Bustarret, F. Freudenberg, R. Hopler, R. Dimitrov, O. Ambacher, and M. Stutzmann., J. Appl. Phys. **82**, 5090 (1997).
[13] See, e.g., G. Malpuech and A. Kavokin, Semicond. Sci. Technol. **16**, R1 (2001), and references therein.
[14] G. Malpuech, A. Kavokin, A. Di Carlo, and J. J. Baumberg, Phys. Rev. B **65**, 153310 (2002).
[15] For large wave vectors (larger than the wave vector of light in the media), the dispersion relation is that of a heavy-hole exciton having an effective mass of $1.2m_e$.
[16] P. Bigenwald, A. Kavokin, B. Gil, and P. Lefebvre, Phys. Rev. B **63**, 035315 (2001).
[17] V. W. L. Chin, T. L. Tansley, and T. Ostochan, J. Appl. Phys. **75**, 7365 (1994).
[18] The radiative efficiency is defined as the ratio of pump power to the emission power of the cavity within a cone of 2°.

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