Coherent emission from exciton-polariton lights

Researchers in Switzerland and the UK have developed a GaN microcavity to produce phenomena that are usually only seen at much lower temperatures in other materials. Dr Mike Cooke describes their achievements and hopes.

Despite the large number of different laser sources available today, finding new techniques is always important. Producing laser light, especially ultraviolet, is often difficult and wasteful of energy due to the high threshold energies resulting from the need to create population inversion.

Researchers from the University of Southampton in the UK and École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland have used an optically pumped exciton-polariton system in bulk GaN microcavities to achieve room-temperature inversionless coherent emission (i.e. lasing without the electron population in the higher 'excited' electron energy level needing to exceed the electron population in the lower energy level to which the electron transitions) [1]. The optical pumping is performed at a non-resonant frequency with a photon energy of about 4eV, while the emission energy is near the GaN exciton emission frequency of 3.4eV, giving an ultraviolet light wavelength of 365nm.

The cavity's optical resonance is tuned to the exciton emission wavelength to create the conditions for the mixing of excitons (electron–hole bound states) and photons into polaritons. The term exciton-polariton is used to distinguish this system of photon mixing from those involving other excitations such as transverse optical phonons (phonon-polaritons).

The emission threshold is an order of magnitude smaller than that for optically pumped (In,Ga)N quantum-well surface emitting lasers (VCSELs). For example, while an optical pumping threshold for lasing of the order 5mJ/cm^2 has been seen in InGaN VCSELs [2], the polariton emission threshold is around 1mW (a pulsed energy density of about 30µJ/cm^2).

One interesting feature of polariton lasers is that lasing without population inversion is possible. This drastically lowers the threshold requirements for such systems. Lasing without population inversion uses quantum coherence effects to reduce reabsorption of emitted light by the medium. The researchers see possible applications for polariton lasers as low-threshold emitters, nonlinear optical elements and amplifiers, and quantum correlated sources.

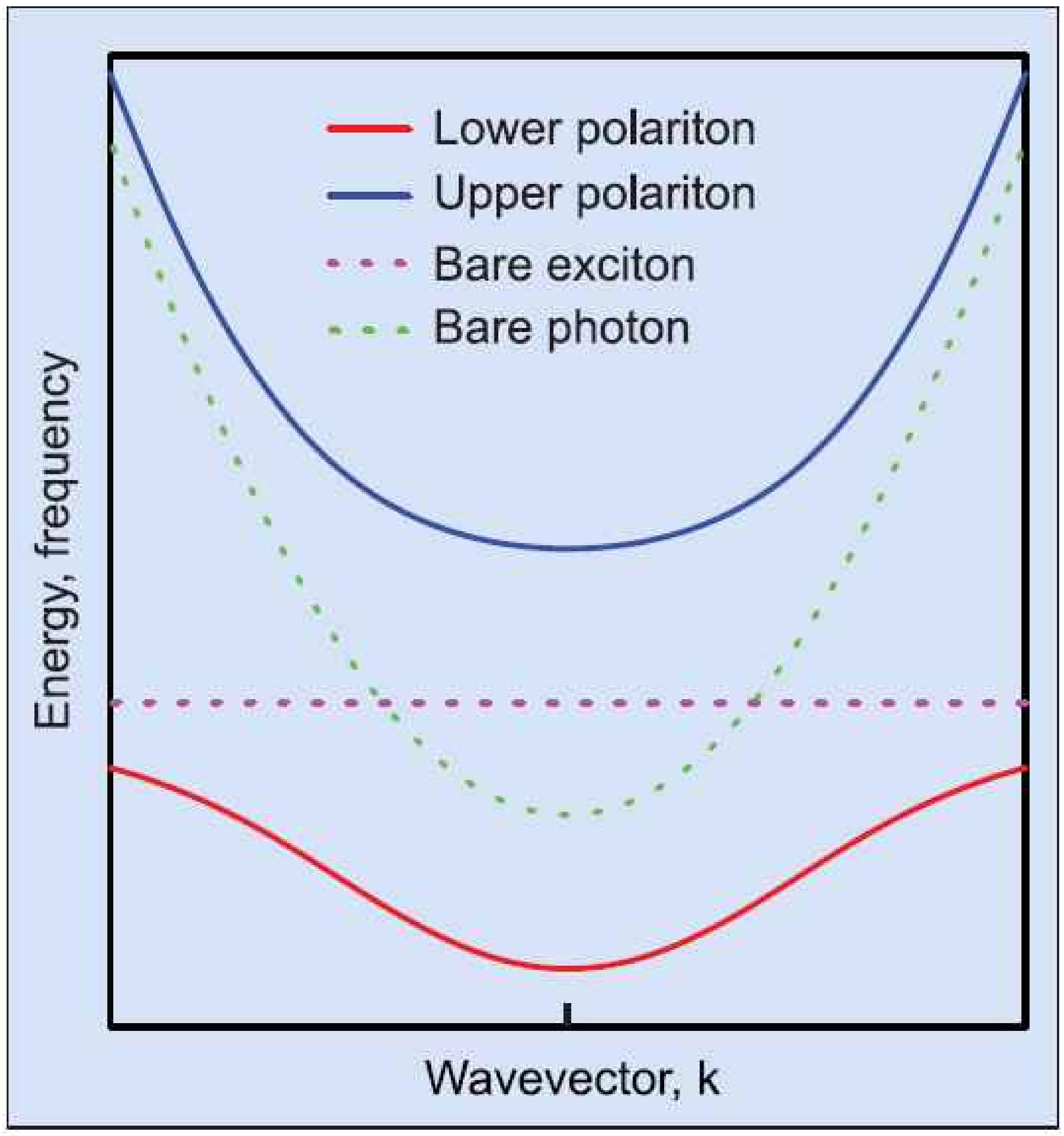

Figure 1. Dispersion relation from coupling between GaN microcavity exciton and photon: vertical axis, polariton energy (or frequency); horizontal axis, wavevector magnitude in the plane of the cavity. For large wavevectors the upper polariton tends to the photon dispersion relation and the lower to the exciton energy (the exciton's kinetic energy is negligible). The cavity thickness (210nm) fixes the wavevector perpendicular to the cavity plane. The 3λ/2 cavity makes the perpendicular wavevector component 45µm^{-1}. The difference between the upper and lower polaritons in GaN is of the order of 50meV. The exciton energy is of the order of 3.4eV. Parallel wavevector scale extends to about 10µm^{-1}.

In 2002, numerical calculations suggested that a GaN microcavity system could meet the properties required to produce polariton lasing [3]. This calculation also suggested that the critical temperature for Bose–Einstein condensation of exciton-polaritons in an n-doped GaN microcavity could be as high as 460K,

room-temperature path to future prospects

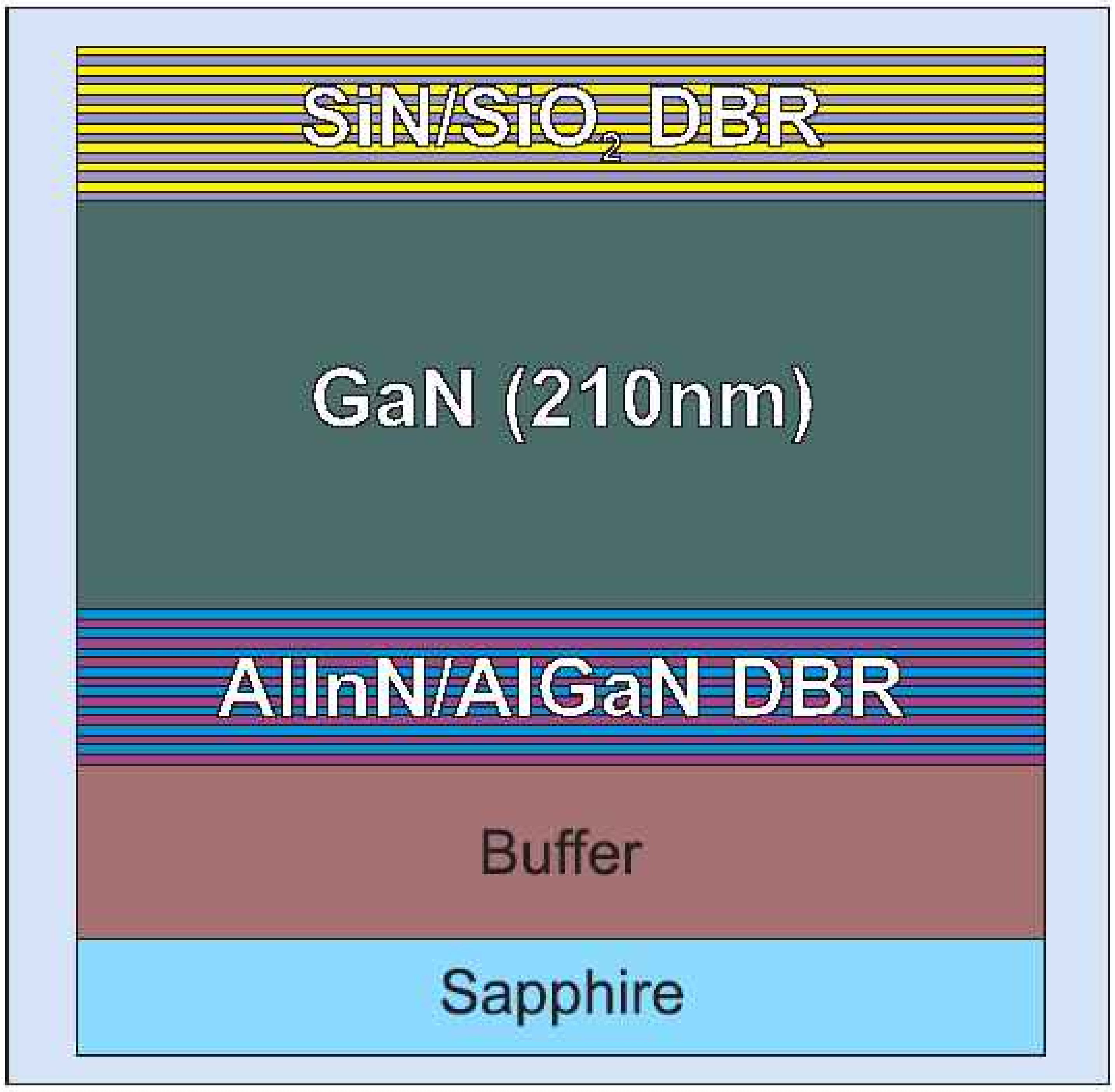

Figure 2. Schematic structure of bulk GaN cavity used to produce polariton lasing.

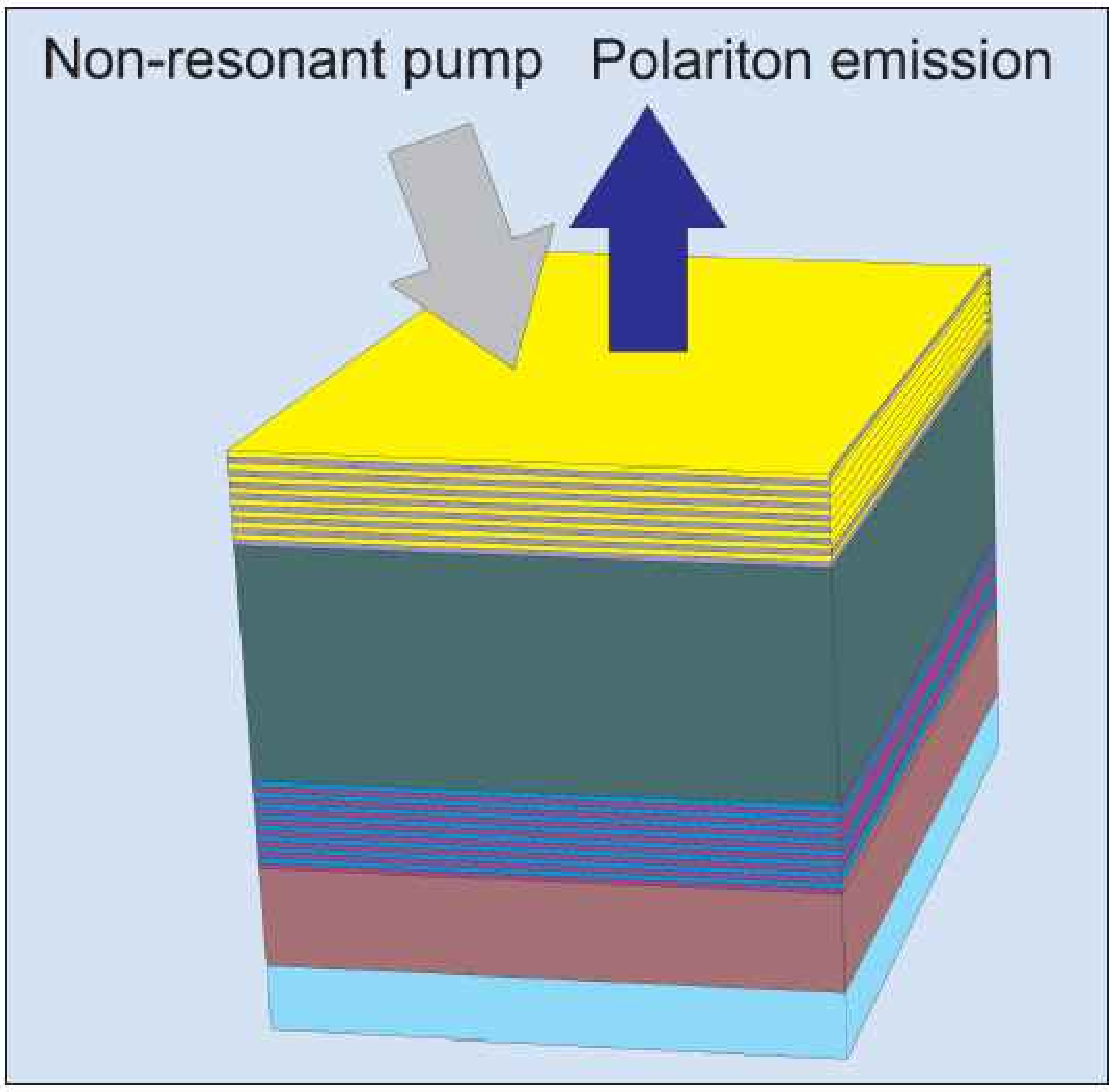

Figure 3. Optical pumping of the polariton laser is performed non-resonantly (4.14eV, λ ~ 300nm) at an angle to the structure to emit UV radiation at 3.4eV (λ ~ 365nm). The optimum angle is about 20°.

compared with a temperature of the order of 100K for GaAs cavity exciton-polaritons or a fraction of a Kelvin for theoretical Mott–Wannier excitons. More recently, cadmium telluride (CdTe) systems have seen polariton emission, but thermal decoherence sets in at 220K, destroying polariton phenomena [4].

A key factor for enabling the raised temperature performance in GaN is its large exciton binding energy (~28meV, equivalent to a temperature of about 325K, compared to about 300K for room temperature). A further key factor is that the exciton–photon coupling (oscillator strength) is much stronger than for other III-V materials. The exciton–photon coupling produces two types of exciton-polariton — upper and lower polaritons (see Figure 1). The splitting for long wavelengths ($\lambda = 2\pi/k$) can exceed 50meV (Rabi splitting) for GaN bulk microcavities, which is an order of magnitude larger than for other III-V semiconductor cavities. In practice, it is the lower polariton that is important for emission — the upper polariton resonance is broadened and almost completely attenuated by the exciton continuum at the same energy.

Despite the theoretical green light, it has taken five years for the researchers to develop the techniques to enable the growth of high-quality cavity mirrors (distributed Bragg reflectors) from GaN alloys (in Switzerland) rather than the more usual SiN/SiO$_2$. The 35-period AlInN/AlGaN bottom DBR is lattice matched with the bulk GaN cavity to reduce strain during growth in order to avoid defects and dislocations (Figure 2). The top mirror is a 10-period SiN/SiO$_2$ DBR.

It was decided to use bulk GaN rather than quantum-well structures. Although QWs allow the optimization of light–exciton coupling, the linewidths for such structures are currently too broad. Further, QW structures in nitride-based semiconductor materials are 'plagued' by the quantum-confined Stark effect (QCSE), where stray electric fields (e.g. piezoelectric fields from strain in the well, small variations in well thicknesses, or alloy composition, etc) can reduce the exciton binding (and hence polariton formation at high temperature) or even break the electrons and holes apart. Another QCSE effect is the strong localization of any exciton states.

Optimum pumping of the structure (Figure 3) was determined to be at an angle of 20° to the sample at

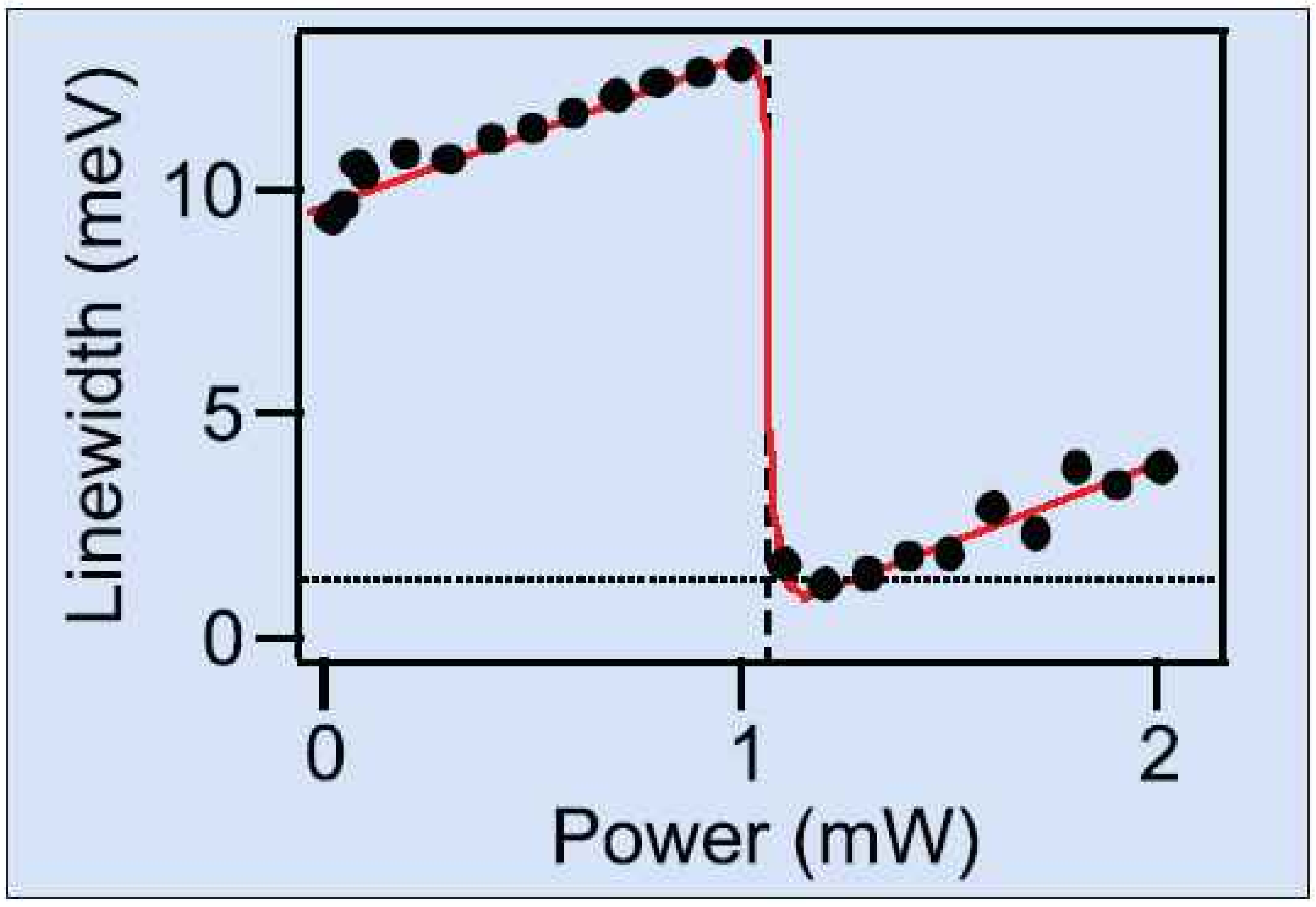

Figure 4. Polariton emission — the linewidth collapses above a threshold intensity of 1mW. The dotted line is the detection limit.

4.14eV. At a pumping power of 4mW, the emitted power is 80µW into a 5° half-width at half maximum (HWHM) cone. These parameters are used to estimate that there are 10^6/polaritons/pulse/state, giving occupations of greater than 10 at threshold. The energy width also collapses at threshold below the detection limit of 1.7meV. The polariton density at threshold is about 10^{18}cm^{-3}.

A number of factors push the polaritons towards coherence. These are mainly various scattering events — the 2002 model [3] used three scattering terms: polariton–acoustic phonon; polariton–polariton; and polariton–electron. In addition, because the polaritons have bosonic statistical properties, stimulated scattering can take place where final states that are already occupied are favored for further scattering events. The polaritons are converted into ultraviolet (365nm) light as they leak out of the cavity. It is the separation of the stimulation and emission that enables lasing without inversion.

Since observation of a threshold (Figure 4) is not sufficient to show coherence of the emission, two further criteria are applied: spatial coherence of the emission spots that collapse from being of the order of the pump spot down to 5µm above threshold (Figure 5); and Michelson interferometry of the resulting light, where fringes continue to be seen, with differences of up to 700fs between the paths (Figure 6). The 700fs delay matches the ultra-short emission lifetime.

These results have implications for creating room-temperature Bose–Einstein condensates (BECs). Although the experiment described here has not strictly achieved this, it is akin to a non-equilibrium BEC. For a strictly defined BEC, one needs thermal equilibrium. "We are optimistic that BECs at room temperature can come soon as the GaN technology progresses through our EPFL colleagues," says Southampton University professor Jeremy Baumberg, one of the researchers.

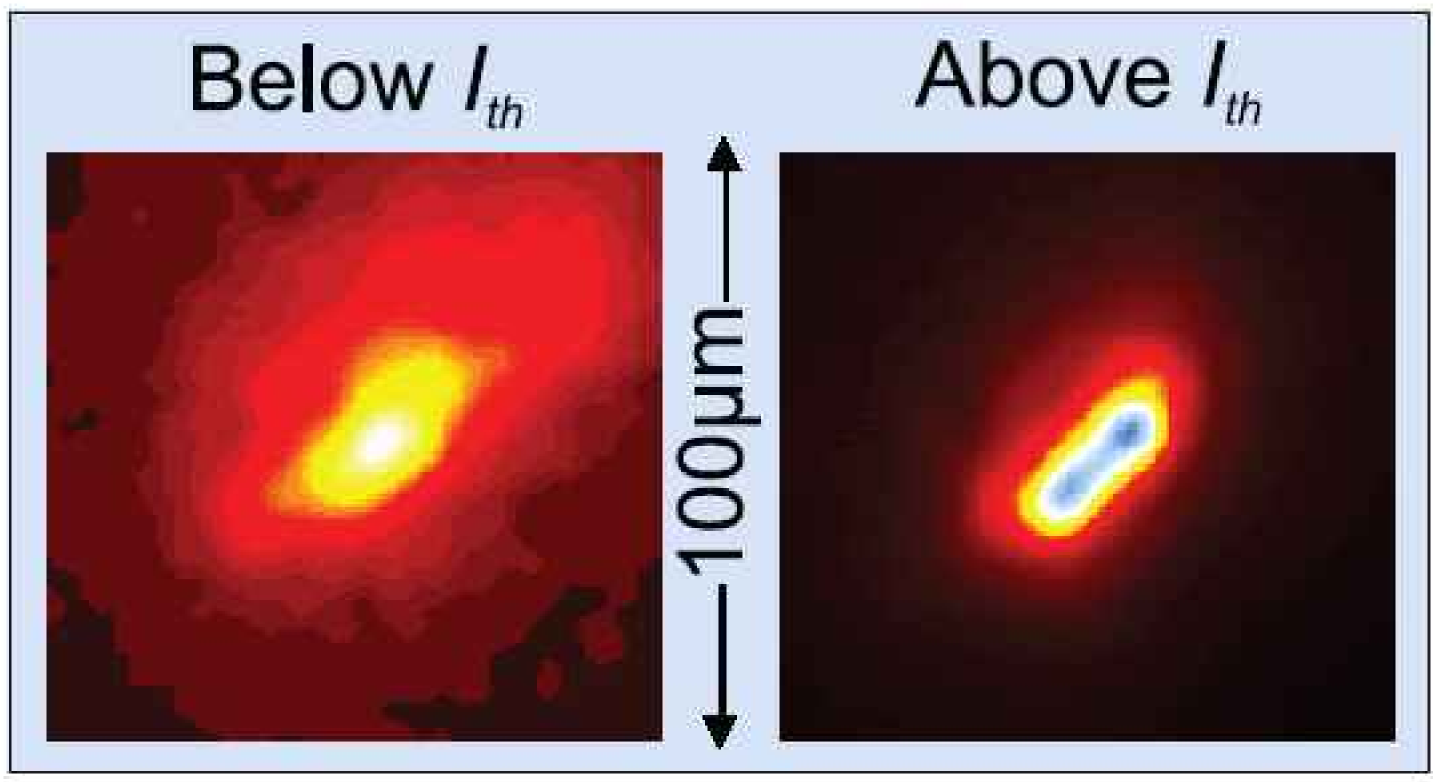

Figure 5. Spatial coherence of the emission spots collapses from being of the order of the pump spot below threshold down to 5µm above threshold.

Baumberg adds: "Such systems would allow construction of interferometer chips for high-precision measurements. But a lot of work remains before such possibilities can be achieved: the GaN material is still under development, and electrical pumping needs to be developed (though in principle there are no roadblocks for this). However, the consistent progress seen over the last seven years indicates the rich potential in basic science and novel technologies awaiting polariton devices."

References

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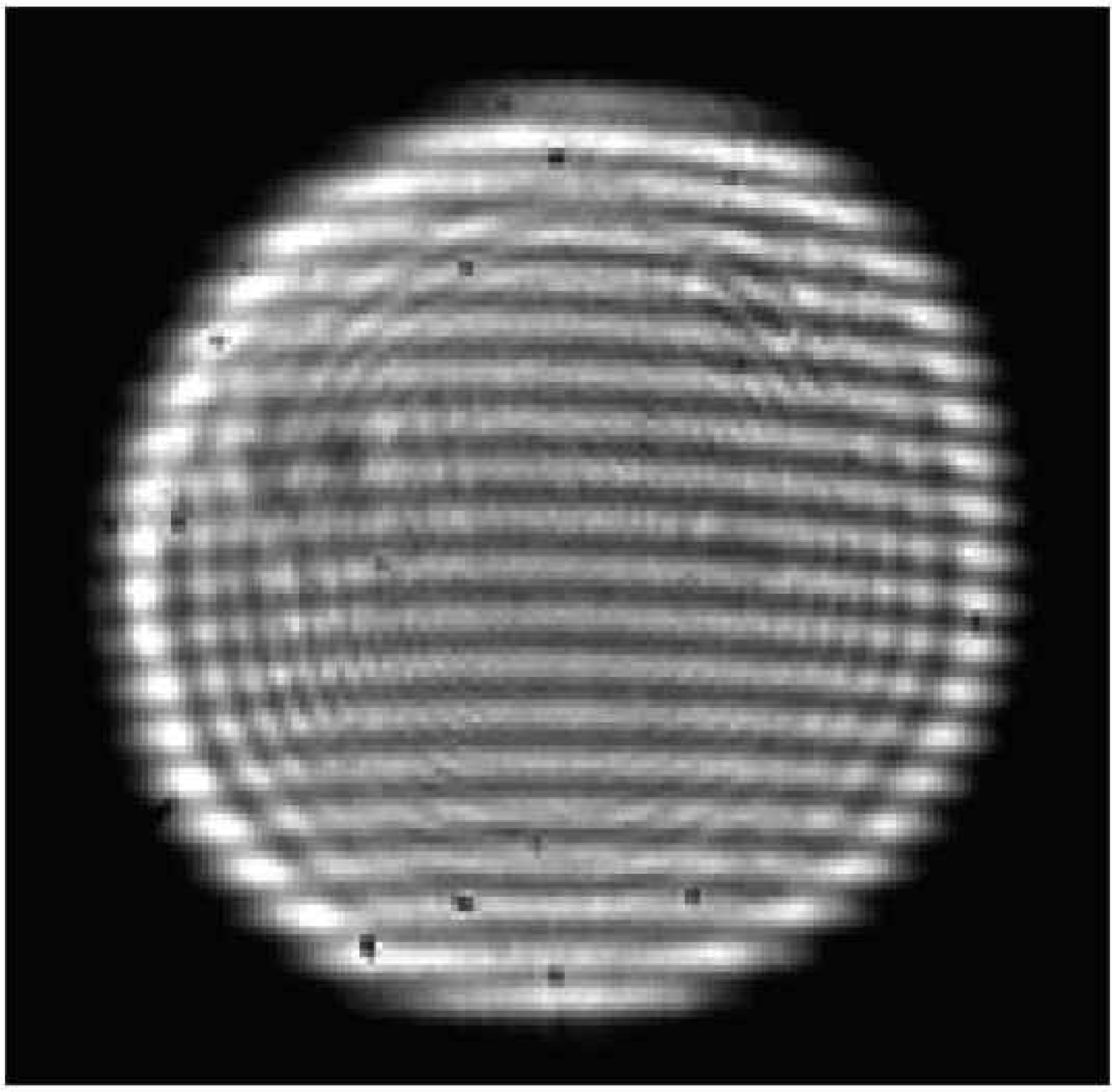

Figure 6. Michelson interferometry k-space image for time delay of 256fs. Coherence of the emission is seen at up 700fs delay between recombined paths.