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Coupling of InGaN quantum well photoluminescence to Silver surface plasmons.

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Abstract

The coincidence of surface plasmon energy on Silver and the GaN bandgap is exploited to couple the semiconductor spontaneous emission into the metal surface plasmons. External efficiency of LEDs could be improved by this process.

Metals support collective oscillations of the conduction electrons - bulk plasmons- at the plasma frequency ω_p. Surface plasmons of a lower frequency ω_{sp} can also be excited by high energy electrons or light. Pioneering studies[1,2] have shown that the fluorescence lifetime of molecules can be affected by a metal surface placed in close proximity. We report the first example of resonant coupling of semiconductor spontaneous emission into surface plasmons, for which $E_{gap} = \supset\omega_{sp}$, where E_{gap} is the semiconductor bandgap.

A 3 nm $In_{0.18}Ga_{0.82}N/GaN$ SQW positioned 12 nm below the surface was used in our photoluminescence (PL) experiments.[3] An 8 nm layer of silver was deposited on only one-half of the sample surface and a 326 nm He-Cd was employed for PL excitation.

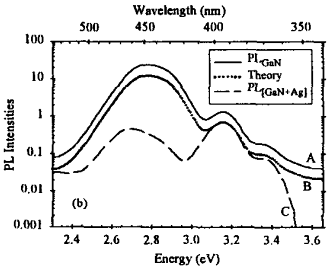

Fig. 1 – SQW PL – Surface Plasmon coupling

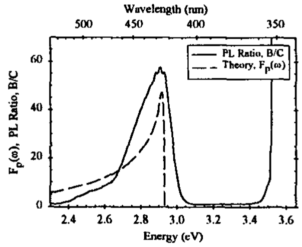

Fig. 2 – Plasmon spectrum and Purcell enhancement factor.

Curve A in Fig. 1 is the PL spectrum measured on the uncoated part of the GaN sample. The SQW PL peak occurs at about 2.8 eV, with a second peak, about 20× smaller, appearing at 3.17 eV. When PL is excited on the Ag-coated part of the sample, the transmission and reflection properties of the Ag layer have to be taken into account, for both the pump light, and the PL emission. This can be calculated easily and curve A can be scaled to simulate the PL emission from the Ag-coated part of the sample, resulting in curve B. The measured PL is however, remarkably different as shown in curve C. At around 3.17 eV the experimental 'C' and predicted 'B' curves coincide, i.e., in this region the usual absorption and reflection properties of silver can indeed account for the PL decrease from curve A. On the other hand, around the 2.8 eV SQW emission, the external PL is reduced by almost two orders of magnitude. We interpret this as spontaneous energy transfer from the SQW electron-hole pairs into the electromagnetic surface plasmon modes of the Silver layer. For energies above 3.4 eV, the excitation of bulk plasmons in Silver produce a strong attenuation of the external PL. A direct measurement of the recombination rate enhancement is given by the ratio B/C, shown in Fig. 2. This ratio, which is an analog of the Purcell[4] factor F_p, can be

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expressed simply as:

$$F_p(\omega) = \frac{\Gamma_p(\omega)+\Gamma_0(\omega)+\Gamma_{nr}(\omega)}{\Gamma_0(\omega)+\Gamma_{nr}(\omega)} \approx 1+\frac{\Gamma_p}{\Gamma_0} \qquad (1)$$

Where $\Gamma_0(\omega)$ and $\Gamma_{nr}(\omega)$ are the radiative and non-radiative recombination rates and $\Gamma_p(\omega)$ is a new spontaneous emission channel into surface plasmons. Γ_{nr} was found to be negligible and was dropped from the right-hand side of eq. (1). $\Gamma_p(\omega)$ can be obtained from Fermi's golden rule:

$$\Gamma_p(\omega) = \frac{2\pi}{\hbar}\langle \mathbf{d}\cdot\mathbf{E}(a)\rangle^2 \rho(\hbar\omega), \qquad \rho(\hbar\omega) = \frac{2\pi k\,dk}{(2\pi)^2 d(\hbar\omega)} L^2 = \frac{L^2}{4\pi}\frac{d(k^2)}{d(\hbar\omega)} \qquad (2)$$

$\rho(\omega)$ is the density of plasmon modes, obtained from the plasmon dispersion relation. We have performed these calculations and the results are shown both in Fig. 2 and on the right side of Fig. 3. Fairly good agreement is obtained between the experimental and calculated spectral shapes in Fig. 2. Both are asymmetric, with a steep slope at high, and a long tail at low energies, and a maximum at 2.9 eV.

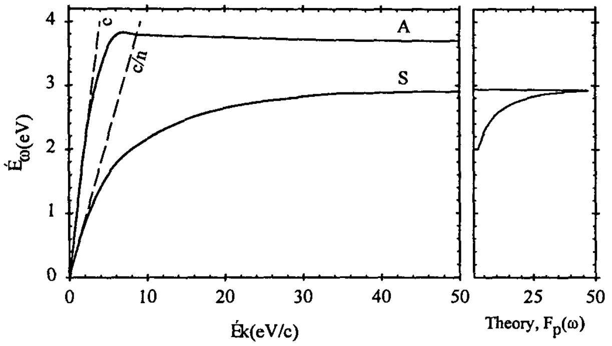

Fig.3 – Surface Plasmon dispersion relation and Purcell factor $F_p(\omega)$.

The plasmon spontaneous emission enhancement, $F_p \approx 49$ (Fig.2) is 15% lower than the experimental $F_p \approx 56$, but considering that the theory has no adjustable parameters, this still is a remarkable result. In addition, the experimental spectrum ($Q \approx 15$) is broader than the calculated curve, ($Q \approx 60$). This might be attributed to Ag film roughness or damping of the electron motion in the Ag.

In summary, we have demonstrated a direct coupling of electron-holes in a 3 nm InGaN/GaN SQW to the surface plasmons of an 8 nm Silver layer spaced 12 nm away from the quantum well. Antenna nanostructures in the thin Ag film might out-couple the SP energy into photons in the air. The result would be > 50 times faster LED modulation efficiency and a spontaneous emission that could be more readily extracted from the semiconductor.

References:

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