JThB5 **6:00 pm**

Waveguiding in Low Index Photonic Crystals

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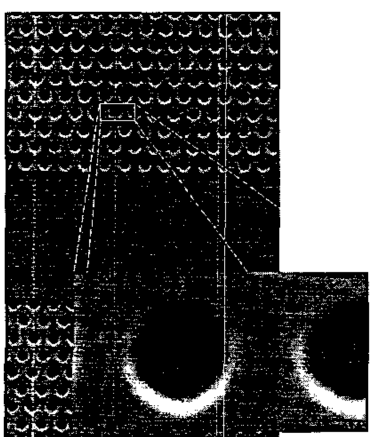
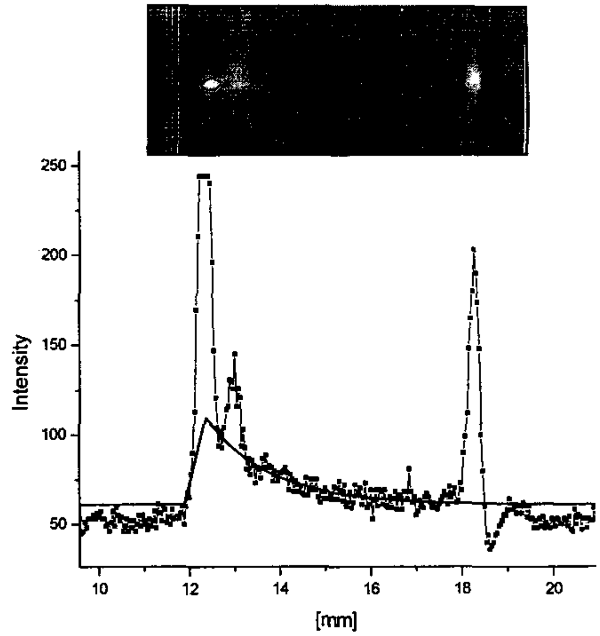
The control of light on a micrometer scale is a subject of active research in contemporary optics. In this context many experimental efforts have focused on the investigation of photonic crystals (PCs). Their inherent potential to suppress light propagation into certain or all directions makes them attractive as new artificial materials for numerous optical applications. In particular waveguides embedded into PCs are predicted to have completely new and exciting properties. Most of the recent experimental studies have concentrated on semiconductors. Their high index contrast with respect to air results in complete gaps in a wide spectral range, therefore allowing for an efficient suppression of radiative losses e.g. in bends and splitters. However, also major problems are caused by the choice of this material system. In particular high losses result from scattering, residual absorption and index mismatch at the fiber-pc interface. Thus, the use of amorphous low index materials, like Nb_2O_5 and SiO_2, has potential advantages. Losses are usually smaller, mature fabrication technologies exist and they fit much better to the well established fiber technology. In this contribution we experimentally demonstrate that waveguiding along defect channels in PC films made from low index materials is possible.



JThB5 Fig. 1. SEM image of the fabricated PC-structure with a defect channel of 5 μm width. The whole structure length is 10 mm.

JThB5 Fig. 2. Near-field distribution of 1550 nm radiation (TE polarized) for defect channel waveguides of 5 μm and 20 μm, respectively.



JThB5 Fig. 3. Measurement of scattered light along a waveguide with a width of 5 μm. The fit shows the exponential decay of the scattered light.

The samples under investigation were made from a layered composite with a waveguiding film consisting of 500 nm of Nb_2O_5 (n = 2.17). A 300 nm-cladding layer and a 2000 nm buffer layer made from SiO_2 (n = 1.43) were used to isolate the guiding region from air and from the silicon substrate, respectively. The structure was kept symmetric to minimize mixing between TE and TM modes. A hexagonal lattice of air holes of 390 nm diameter and of 620 nm separation was etched 800 nm deep into the structure. This PC-structure is designed to have a maximum gap for TE-polarized light around an operation wavelength of 1550 nm. Waveguides of varying widths between 5 and 100 μm were formed by leaving stripes along the ΓK direction of the crystal unstructured (see Fig. 1).

While the PC blocks all TE-polarized light at the operation wavelength of 1550 nm, all waveguides transmitted TE-waves (see Fig. 2). The losses amount to ≈20 dB for a structure length of 6 mm (including coupling losses). This is in good agreement with measurements of the scattered light along the waveguide (see Fig. 3). In contrast, the TM transmission is much lower, depending on the width of the waveguide. While the TM transmission is about 50% of the TE value for wide waveguides (20 μm), it reduces to <10% for the narrow guides (5 μm). This can be explained on the basis of the band structure of the PC. At the operation wavelength TM-waves have no gap. Hence light propagating in the channels can enter the PC causing a damping of the guided mode. This effect becomes even more pronounced for narrower guides, were the interaction of light with the PC-interface is more intense.

In conclusion we have experimentally demonstrated waveguiding along defect channels in PC films made from low index materials. The waveguiding losses are below 3.5 dB/mm. A proper design of the basic crystal allows for a polarization sensitive transmission of the guides.

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Light Sources for Photonic Circuitry Based on Si

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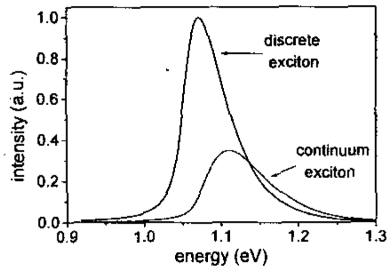
1. Introduction

Photonic band gap materials, or simply called photonic crystals, had recently attracted many attentions for their potential of controlling light wave in a way similarly to semiconductors controlling particle waves of carriers.[1] With intentionally designed defects, light cavities, wave-



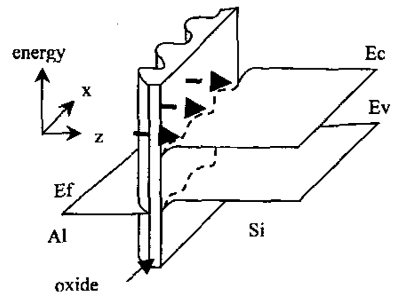
JThB6 Fig. 1. Theoretically calculated phonon-assisted luminescence spectra from the discrete states and the continuum states of exciton at 300 K, respectively.

guides, reflectors, filters, and other functional components can be integrated in the same photonic crystals. Thus they will form photonic circuitry, performing functions similar to the roles played by electronic circuitry. To have the full functions, light sources are also important. On the other hand, the mature fabrication technology using Si could possibly help the spread of photonic circuitry based on Si. However, light generation from Si is hindered by the indirect-bandgap nature. Here we report the possibility of breaking the indirect-bandgap limitation to efficiently generate light from Si. We theoretically and experimentally discovered that carrier localization could enhance radiative recombination corresponding to bandgap energy of Si for orders of magnitudes. Nearly lasing actions corresponding to Si bandgap energy were even observed with the enhanced radiative recombination.

2. Theoretical model for efficient radiative recombination in Si

Because of the indirect-bandgap nature of Si, the probability of electron-hole recombination is very low without the involvement of phonon. However, the phonon involvement causes the process to be like simultaneous collision of three particles (electron, hole, and phonon), so the probability is also very low. If an electron and a hole already form an exciton, the process will be like two-particle collision, exciton vs. phonon. The probability then greatly increases. Based on such concept, we derive the following formula for the emission from Si with phonon and exciton involvement.[2]

$$S(\hbar\omega) \sim \sum_n \frac{1}{(2\pi)^3} \iint_{Kq} d^3K d^3q \cdot |\phi_n(r=0)|^2 \cdot L\left(E_g - \frac{E_B}{n^2} + \frac{\hbar^2K^2}{2M} - E_p - \hbar\omega\right) \cdot \delta(\vec{q} - \vec{k}_e - \vec{k}_h) \cdot \frac{1}{\exp\left(\dfrac{E_g - \dfrac{E_B}{n^2} + \dfrac{\hbar^2K^2}{2M} - F_x}{k_BT}\right) - 1}$$



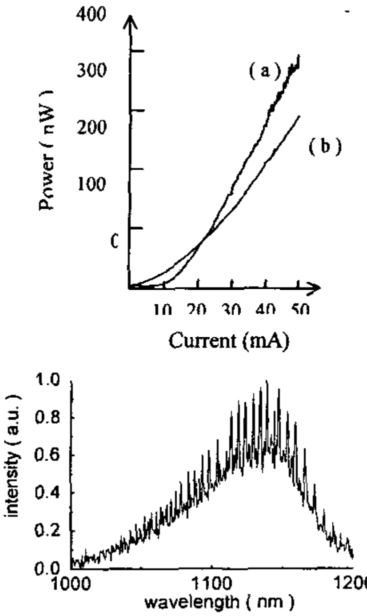
JThB6 Fig. 2. Two-dimensional (x-z) schematic of the band structure for nanoparticle-modified MOS under forward bias. The behavior along the y-axis is similar to that along the x-axis. The dashed arrows point to the regions with the thin oxide, where more holes tunnel to Si.

$$+ \frac{1}{(2\pi)^3}\frac{1}{(2\pi)^3} \iiint_{kKq} d^3k d^3K d^3q \cdot |\phi(r=0)|^2 \cdot L\left(E_g + \frac{\hbar^2k^2}{2\mu} + \frac{\hbar^2K^2}{2M} - E_p - \hbar\omega\right) \cdot \delta(\vec{q} - \vec{k}_e - \vec{k}_h) \cdot \frac{1}{\exp\left(\dfrac{E_g + \dfrac{\hbar^2k^2}{2\mu} + \dfrac{\hbar^2K^2}{2M} - F_x}{k_BT}\right) - 1}$$

The first and second terms are contributed from the discrete states and the continuum states of exciton, respectively. The calculated contributions are shown in Fig. 1. The discrete states have stronger emission than the continuum states because the electron and the hole are more tightly bonded together in the discrete state, giving a better chance of simultaneous collision with phonon. On the other hand, the localization of electrons and holes in the same region is similar to excitons, or possibly helps the formation of excitons. The probability of radiative recombination thus also increases.

3. Experiments

To have the localization of electrons and holes in the same region, we use nanoparticles in the oxide layer of the conventional metal-oxide-semiconductor (MOS) structures. The nanoparticles cause the thickness of the oxide layer to be nonuniform and lead to the following two effects. First, as the MOS structure is forward biased, the band bending of Si toward the thin oxide is more severe than the thick oxide, resulting in three-dimensional potential wells for carrier confinement, as shown in Fig. 2. Second, in the region with the thin oxide, more carriers tunnel to Si through the thin oxide layer than through the thick oxide layer. As a result, electrons and holes



JThB6 Fig. 3. (left) L-I curves: (a) with threshold; (b) without threshold. (right) Measured spectrum with resonance modes, corresponding to curve (a).

have the similar spatial confinement near the Si/SiO_2 interface.

The above mechanisms significantly enhance the electroluminescence. The measured differential quantum efficiency could be as large as 10^{-4} at the low the current density of $1.67\ A/cm^2$. There is still great portion of light blocked by the bonding pad, so the actual efficiency is better than 10^{-4}. Nearly lasing actions like the threshold behavior and resonance modes are also observed, as shown by the L-I curve (a) in Fig. 3. For comparison, the L-I curve of another device without threshold is shown by curve (b). The corresponding spectrum for L-I curve (a) is shown in the right figure. The resonance modes are clearly shown. In contrast, no resonance modes are observed for all of the devices without the threshold behavior. The details will be discussed.

References

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