

# Polarization of lasing emission in microdisk laser diodes

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TE polarization of optical emission from microdisk laser diodes of radius  $R=5\ \mu\text{m}$ , thickness  $L=0.3\ \mu\text{m}$ , is found to dominate both below and above room-temperature lasing threshold current,  $I_{\text{th}}=2\ \text{mA}$ . TE emission in the lasing mode at  $\lambda=1560\ \text{nm}$  wavelength is due to higher optical gain for TE modes in the quantum well device. In our device geometry, the intrinsic whispering gallery resonances have essentially no polarization selectivity. © 1995 American Institute of Physics.

Future integrated optoelectronic devices will make use of very small, power efficient laser diodes with optical emission guided either in or out of the semiconductor substrate plane. Devices with high- $Q$  optical resonant cavities and large overlap between lasing mode photon intensity and semiconductor gain medium are needed to meet these requirements. In addition, polarization of lasing emission must be specified to ensure proper design of wave guides, couplers, and other polarization sensitive applications.

Recently, there has been interest in these microlaser design issues. New microdisk<sup>1,2</sup> and microcylinder<sup>3</sup> resonant cavities making use of whispering-gallery optical modes characterized by azimuthal mode numbers  $M$  and radial mode numbers  $N$  have been studied with lasing emission wavelength at  $\lambda=1550$ ,<sup>4</sup>  $\lambda=980$ ,<sup>3</sup> and  $\lambda=510\ \text{nm}$ .<sup>5</sup> Techniques to control polarization of lasing emission from the more established vertical cavity surface emitting laser (VCSEL) has also been a subject of recent research.<sup>6</sup>

We report the first measurements of polarization of optical emission from microdisk laser diodes. We compare our results with similar measurements performed on conventional Fabry–Perot laser diodes fabricated from the same InGaAs/InGaAsP quantum well material.

Figure 1 shows a scanning electron microscope (SEM) micrograph of the microdisk laser diode similar to that used in this study. The quantum well semiconductor material was grown by metalorganic chemical vapor deposition (MOCVD) with the layer structure given in Table I. Microdisk laser diodes were fabricated by photolithography defining  $p$ -type metal contacts and dry etching cylinders of radius  $R=5\ \mu\text{m}$ . Selective HCl-based chemical etching of the InP layers was used to create two circular disks supported by InP pillars of rhombihedral cross section. The middle disk shown in Fig. 1 has thickness  $L=0.3\ \mu\text{m}$  and contains multiple quantum wells with refractive index  $n_{\text{QW}}=3.44$  at  $\lambda=1550\ \text{nm}$ . The upper disk is a 300 nm thick  $p$ -type InGaAs layer on which AuBe is deposited and alloyed for the  $p$ -type Ohmic contact. An alloyed NiGeAu  $n$ -type Ohmic contact is made on the back side of the InP substrate.

Polarization resolved light intensity versus injected current ( $L$ - $I$ ) is measured at room temperature by collecting a portion of optical emission with a 0.3 numerical aperture,  $\times 40$  magnification, lens placed in the plane of the substrate.

The collimated beam passes through a polarizer with  $\sim 1000:1$  polarization selectivity and collected light intensity is measured using a broad area Ge detector.

Figure 2 shows  $L$ - $I$  data for TE ( $E$ -field polarization in the plane of the substrate) and TM polarizations. A kink in the TE curve occurs at the threshold current  $I_{\text{th}}=2\ \text{mA}$ . Overall, the TM emission is suppressed, however, there is a continuous increase in emission with increasing injection current. The inset in Fig. 2 shows spectra for an injection current of  $I=4\times I_{\text{th}}=8\ \text{mA}$  with spectrometer resolution 5 nm. Spontaneous emission with a small TE polarization selectivity is observed between 1200 and 1600 nm. Lasing occurs at wavelength  $\lambda_{50,38}=1560\ \text{nm}$  with peak power level 1000 times higher than the background and TE/TM emission intensity selectivity of 10. We label the peak  $\lambda_{50,38}$  since we calculate it corresponds to  $M=50$  for TE field with  $n_{\text{eff}}(\text{TE})=2.84$  and  $M=38$  for TM field with  $n_{\text{eff}}(\text{TM})=2.18$ , respectively.<sup>1</sup> For such high order modes it is expected the optical intensity is concentrated in a narrow annulus about  $0.5\ \mu\text{m}$  wide near the disk's edge. Higher resolution spectra allowing clear distinction between TM spontaneous emission linewidth and a much narrower TE laser emission linewidth were not possible due to spectrometer throughput limitations.

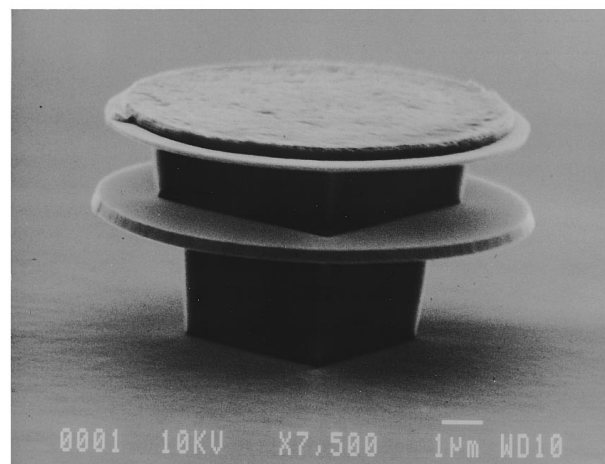


FIG. 1. Scanning electron microscope micrograph of a microdisk laser diode. The device has a radius of about  $5\ \mu\text{m}$  and electrical current is injected from the top metal contact.

TABLE I. Epitaxial layers grown by MOCVD for the devices used in this work. The band-gap wavelength of the InGaAsP material is  $\lambda_g = 1150$  nm.

Material	Thickness ( $\mu\text{m}$ )	Impurity concentration ( $\text{cm}^{-3}$ )
InGaAsP	0.3	$p = 3 \times 10^{18}$
InP	1.5	$p = 2 \times 10^{18}$
InGaAsP	0.11	$i$
InGaAs	0.0096	$i$
InGaAsP	0.0105	$i$
InGaAs	0.0096	$i$
InGaAsP	0.0105	$i$
InGaAs	0.0096	$i$
InGaAsP	0.11	$i$
InP	0.7	$n = 2 \times 10^{18}$
InP	Substrate	$n = 3 \times 10^{18}$

We have also fabricated standard Fabry-Pérot buried heterostructure lasers from the same wafer. Figure 3 shows the polarization resolved  $L$ - $I$  plot for one of these devices. The solid line shows as-measured TM light intensity (note the  $\times 100$  scale) while the dashed line is corrected for the polarizer's finite TE rejection. The inset shows spectra for both polarizations taken with 5 nm resolution at a steady state injection current of  $I = 2 \times I_{th} = 50$  mA. Laser emission is observed at wavelength  $\lambda = 1544$  nm for the TE mode. The peak at  $\lambda = 1544$  nm in the TM spectra is due to the finite polarizer's selectivity. Carrier pinning, as evi-

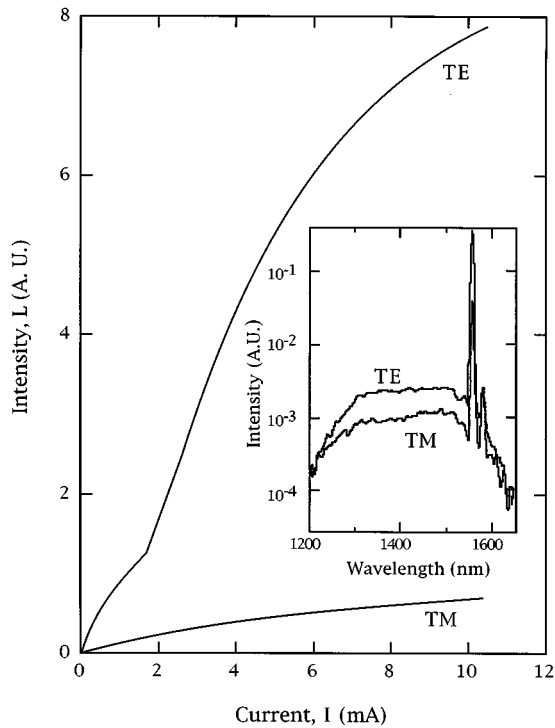


FIG. 2. Measured room-temperature polarization-resolved light intensity vs injected current for the microdisk laser diode shown in Fig. 1. The inset shows the polarization resolved spectra obtained with 5 nm resolution. The injection current is  $I = 4 \times I_{th} = 8$  mA and emission peak at wavelength  $\lambda_{50,38} = 1560$  nm is observed for both polarizations.

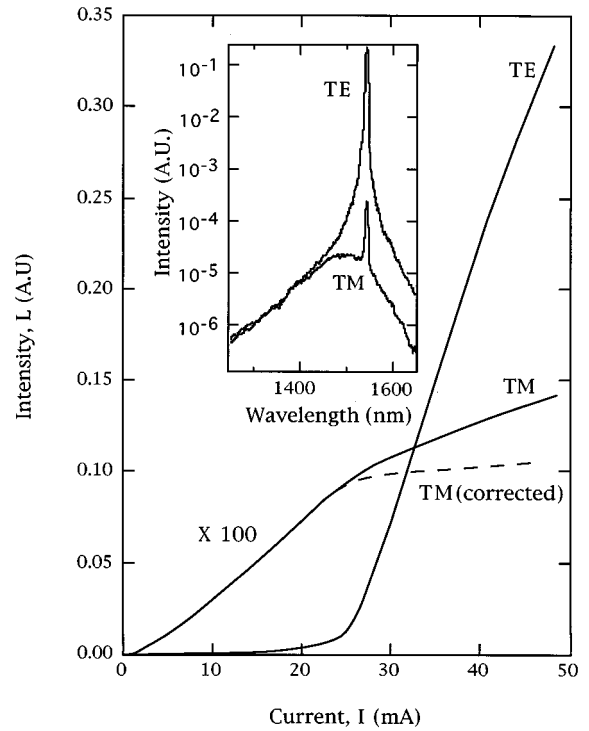


FIG. 3. Measured room-temperature polarization-resolved light intensity vs injected current for a conventional Fabry-Pérot laser with a cavity length of  $L_c = 340$   $\mu\text{m}$ . The vertical scale of the TM mode is  $\times 100$ . The dashed line shows the TM  $L$ - $I$  plot after subtracting the TE contribution not rejected by the polarizer. The inset shows the polarization resolved spectra obtained with 5 nm resolution. The injection current is  $I = 2 \times I_{th} = 50$  mA and laser emission peak at wavelength  $\lambda = 1544$  nm is observed for TE polarization. The peak observed in the TM spectra at this same wavelength comes from TE emission and is due to polarizer limited selectivity.

denced by fixed TM emission above  $I_{th}$ , is clearly very efficient in the Fabry-Pérot laser diode. In the microdisk structure, however, the observed increase in spontaneous recombination with increasing injection current arises from poor overlap between the lasing optical mode, mostly at the edges of the disk, and the carrier distribution at the center of the device. Thus, the carrier distribution in the central region of the microdisk is effectively decoupled from the laser's active region at the perimeter of the disk.

The TE emission selectivity in conventional Fabry-Pérot lasers arises mainly because (cleaved) mirror reflectivity is largest for these modes.<sup>7</sup> In addition, unstrained quantum well active regions have a small probability of optically induced TM transitions.<sup>8</sup> Allowed TM optical emission due to conduction band to light-hole band carrier recombination is suppressed due to the small number of occupied light-hole states. Overall the greater available optical gain for TE modes constitutes a geometry independent polarization selectivity in these quantum well structures. The same reasoning applies to microdisk laser diodes.

Nevertheless, geometrical considerations should also be considered when discussing polarization selectivity in microdisk lasers. Previous work<sup>9</sup> on thickness dependence of polarization in slab waveguides suggests that our structure with  $L > \lambda n_{QW} / 2$  should have no polarization selectivity in the spontaneous emission rate. Unfortunately, this previous work

failed to take into account polarization selection rules in the quantum well active gain medium.

For polarization selectivity in the microdisk's resonant optical modes one also has to study light reflection at curved dielectric interfaces. The resonant modes of a microdisk impinging at the disk's edge with an off-plane angle  $\beta$  given by the confinement perpendicular to the disk's plane and a glancing angle  $\alpha(M)$ . Since optical confinement in the direction perpendicular to the disk's plane is very high ( $\approx 90\%$ ),  $\beta \approx 0$  for both TE and TM modes resulting in a polarization independent reflectivity in the perpendicular direction.<sup>7</sup> The glancing angle  $\alpha$  is related to a whispering gallery mode  $M$  by  $\alpha = (M-1)\pi/2M$  corresponding to a polygonal optical path with  $2M$  sides. Higher order modes have greater incidence angle approaching  $\alpha = 90^\circ$  as  $M$  approaches infinity. Snyder and Love<sup>10</sup> showed that optical transmission  $T(\alpha)$ , at a curved interface is related to the polarization dependent Fresnel coefficient for planar interfaces,  $T_F(\alpha)$ , via  $T(\alpha) = |T_F(\alpha)|^2 C(\alpha)$ , where  $C(\alpha)$  is a polarization independent curvature coefficient. For  $\alpha$  smaller than the critical angle  $\alpha_c$ , polarization selectivity is given by  $T_F(\alpha)$  resulting in a situation identical to that for planar interfaces. However, when  $\alpha > \alpha_c$ ,  $T_F(\alpha) = 1$  for both polarizations, and no selectivity exists. For our device  $n_{\text{eff}} = 2.18$  for TM and  $n_{\text{eff}} = 2.84$  for TE, the critical angle becomes  $\alpha_c = 27^\circ$  and  $\alpha_c = 21^\circ$ , respectively. These angles are much smaller than the incidence angles of whispering gallery modes. Therefore, we conclude that no polarization enhancement can be attributed to resonant cavity effects.

Optical emission from the microdisk originates from essentially two processes. First, somewhat polarized TE spontaneous emission generated anywhere inside the disk propagating outwards in nonwhispering gallery modes with high optical transmission ( $\approx 80\%$ ) and incidence angles smaller than  $\alpha_c$ . This emission gives the TE polarized spontaneous

emission background shown in Fig. 2. Second, lasing whispering gallery modes appear as sharp peaks with higher TE emission largely due to the greater TE stimulated emission rate. Figure 2 shows emission at  $\lambda_{50,38} = 1560$  nm where a selectivity of 10 is observed. By contrast, the Fabry-Pérot laser has about 1000 times more polarization selectivity due to a strong cavity (mirror induced) TE mode selection.

In conclusion, we report the first measurements of optical emission polarization selectivity in microdisk laser diodes. TE-polarized lasing at 1560 nm wavelength is observed for a disk of radius  $R = 5 \mu\text{m}$ , thickness  $L = 0.3 \mu\text{m}$ . The suppressed TM-polarized emission shows evidence of weak carrier pinning for above lasing threshold currents due to a small overlap between resonant modes near the edge of the disk and the central pumped region. TE emission in the lasing mode is largely due to higher optical gain in quantum wells for TE modes since whispering gallery resonances per se have essentially no polarization selectivity.

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