Thermo-optic tuning of erbium-doped amorphous silicon nitride microdisk resonators

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We demonstrate a technique to yield a direct and sensitive measurement of the thermo-optic coefficient (TOC) for light-emitting materials in optical microdisk resonators. Using photoluminescence from erbium-doped amorphous silicon nitride (a-SiN$_x$:Er) as an example, we show how the TOC can be extracted from thermally induced shifts in the resonant microdisk modes. For the highest-performance a-SiN$_x$:Er material composition, we find a TOC at 1.54 μm of $\sim 3 \times 10^{-5}$ K^{-1} in the 300–500 K range. Additionally, our work demonstrates a convenient all-optical spectroscopic technique for sensitive temperature measurements, with a resolution of $\sim$30 mK in this temperature range. © *2011 American Institute of Physics*. [doi:10.1063/1.3545845]

A precise quantification of how an optical material's refractive index scales with temperature—that is, the thermo-optic effect—is crucial for the effective design of integrated optoelectronic components, although it may be regarded as either a feature to be exploited (e.g., in tunable sources, modulators, filters, and sensors) or a problem to be addressed (e.g., in waveguides, interferometers, and lasers).[1] This temperature-induced index variation is described by the material's thermo-optic coefficient (TOC), $\partial n/\partial T$. While the TOC can be measured using prism-based, diffraction-grating-based, and étalon-based techniques,[1] we describe in this letter a method to measure the TOC in arbitrary light-emitting materials by incorporating them into pedestal-supported microdisk resonators [Fig. 1(a)]. The resonant optical modes supported by a microdisk can be classified by the number of nodes present in the radial ($\hat{r}$), axial ($\hat{z}$), and azimuthal ($\hat{\phi}$) directions, given by the integer mode numbers n_r, n_z, and m, respectively; the cylindrical symmetry of the system imposes an $e^{-im\phi}$ azimuthal dependence on these so-called *whispering-gallery modes* (WGMs).[2] In this microdisk-based TOC measurement, the photoluminescence (PL) of the disk material itself acts as the probe, eliminating the need for an external probe laser: the PL couples to WGMs propagating near the disk circumference [inset of Fig. 1(a)], whereupon shifts in a particular WGM's spectral position λ_{res} can be mapped to a change in the microdisk's index via comparison with theory.

This approach is attractive for several reasons. (1) The TOC is determined in a realistic laser resonator architecture[3] rather than in an *ad hoc* specimen (e.g., a prism or diffraction grating fabricated out of the test material), and so includes any changes to the material's optical properties resulting from processes used in microdisk laser fabrication. (2) With appropriate choice of microdisk size, it is possible to have many WGMs supported within the emission band of the test material, allowing the TOC to be monitored at several wavelengths simultaneously in one spectral measurement. (3) Small, thermally induced shifts in λ_{res} can be measured with great precision due to the narrow WGM linewidths possible in high-quality-factor microdisk resonators. This last reason also suggests the appealing application of using integrated microdisks as spectroscopic local temperature sensors: after calibration, monitoring λ_{res} directly yields the *actual* device temperature, an approach which is much more accurate than approximating the specimen temperature by that of its surroundings (from a cryostat setpoint, etc.).

While this method generalizes conveniently to any light-emitting material capable of being patterned into a microdisk, we will illustrate it using erbium-doped amorphous silicon nitride (a-SiN$_x$:Er). This material has garnered recent interest for silicon-based optoelectronic applications due to its efficient PL at 1.5 μm, nanosecond-scale energy transfer from the sensitizing a-SiN$_x$ host to the Er^{3+}, homogeneous microstructure, improved electrical injection and electroluminescence with respect to oxide-based nanocomposites, and weak thermal PL quenching.[4,5] Optical resonator structures such as microdisks[6] and photonic crystal cavities[7] incorporating a-SiN$_x$:Er have also been reported, demonstrating its utility as a potential gain material for on-chip, Si-based lasers. By using an optimized a-SiN$_x$:Er film composition as the example for our microdisk-based TOC method, we there-

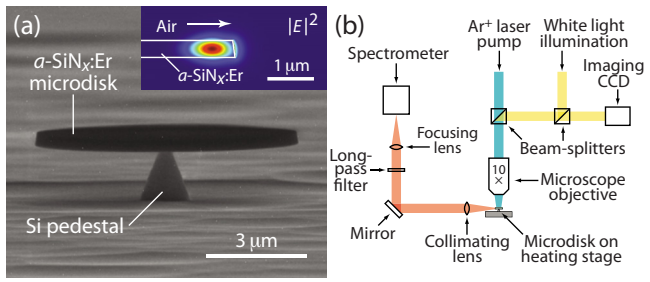

FIG. 1. (Color online) (a) Scanning-electron micrograph of the microdisk used in this study. Inset: finite-element full-field simulation of the electric field intensity for the TE_{22} mode; the dominant electric field direction is shown with an arrow. (b) Schematic of experimental apparatus.

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fore also quantify an effect relevant to photonics designs using an exciting optical material.

To fabricate the pedestal-supported a-SiN_x:Er microdisk resonators, a 360-nm-thick a-SiN_x:Er film was first deposited on a (100) Si substrate via reactive magnetron cosputtering of Si and Er targets using a N_2/Ar mixture for the process gas.[8] In this technique, the film stoichiometry can be controlled by changing the N_2/Ar flow ratio; from Rutherford backscattering spectrometry, the as-deposited film was determined to be nearly stoichiometric Si_3N_4, with an Er concentration of $\sim 3\times 10^{20}$ cm^{-3}. Next, a 100-nm-thick layer of chromium was deposited via electron-beam evaporation as a hard mask and patterned into circular regions with diameters ranging from 1 to 100 μm using photolithography followed by wet-etching. This disk pattern was transferred to the a-SiN_x:Er layer by dry-etching down to the Si substrate in a NF_3/Ar plasma. After removing the Cr mask via wet-etching, the pedestals were defined by undercutting the Si in a 25% tetramethylammonium hydroxide etch solution at 90 °C. Finally, the finished microdisks were annealed in a quartz tube furnace at 1140 °C for 120 min in N_2. This combination of film composition and thermal processing conditions has been determined to yield the most intense emission and longest lifetime (highest internal quantum efficiency) at 1.5 μm,[4] and therefore represents an optimum a-SiN_x:Er film.

A scanning electron micrograph of a microdisk with diameter $D_{disk}=7.7$ μm is shown in Fig. 1. By performing spectroscopic ellipsometry and modeling the film as a Cauchy material with Urbach absorption[9,10] (WVASE32® software, J. A. Woollam), the annealed a-SiN_x:Er layer was determined to have a thickness of 360 nm and a room-temperature (RT) refractive index of $n=2.059$ at 1535 nm. The microstructure of these films has been reported previously;[8] from high-resolution transmission electron microscopy and selected-area electron diffraction studies, it was determined that the annealed film does not contain any crystalline silicon nanoclusters, although the presence of very small (<2 nm diameter) amorphous clusters cannot be ruled out.

The apparatus used to measure the microdisk PL is schematized in Fig. 1(b). The microdisk, mounted on a resistive heating stage with fine xyz translation control, was pumped optically with the 488 nm line of a continuous-wave argon-ion laser focused with a 10× microscope objective. Alignment of the excitation laser (~6.5 μm spot size) was made possible by imaging the microdisk using a charge-coupled device camera. Full-field modeling of the resonant microdisk modes showed that the far-field radiation pattern is predominantly in the plane of the microdisk;[2] accordingly, the collection optics were placed in this orientation to collect the WGM emission most efficiently. PL emitted from the microdisk edge was collimated using a 2-in.-diameter plano-convex lens, passed through a 550 nm long-pass filter to reject the pump laser light, and focused onto the input slit of a spectrograph equipped with a liquid-nitrogen-cooled InGaAs photodiode array for spectral analysis. The substrate temperature was adjusted by fixing the input voltage for the resistive heater and waiting ~30 min for stabilization, monitored with a K-type thermocouple attached to the heater surface (±2 K error). From pump-intensity-dependent measurements (not shown), we determined that there is negligible laser-induced heating of the microdisk for $\Phi_{ex}<6$ kW/cm^2; Φ_{ex} was therefore fixed at ~1 kW/cm^2 for this study.

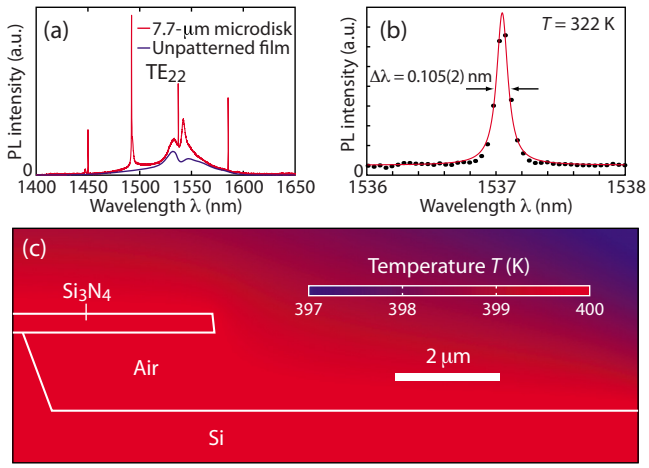

FIG. 2. (Color online) (a) RT PL spectra of a-SiN_x:Er film and microdisk ($D_{disk}=7.7$ μm). (b) Background-subtracted TE_{22} mode spectrum. (c) Simulated steady-state temperature map near microdisk for $T_{substrate}=400$ K.

Figure 2(a) displays typical, RT, steady-state PL spectra from an unpatterned a-SiN_x:Er film and the microdisk shown in Fig. 1(a), scaled arbitrarily for ease of comparison. In the microdisk spectrum, several sharp WGM resonances are visible superimposed on the background $^4I_{13/2}\rightarrow{}^4I_{15/2}$ Er^{3+} emission band.[4] In particular, the RT TE_{22} mode ($m=22$, $n_z=n_r=0$) is supported at 1536.7 nm at RT, near the peak of the emission band; we will focus on this mode for the remainder of this study. To ensure that the measured substrate temperature was representative of the temperature of the microdisk itself, we used a finite-element tool to calculate the steady-state temperature of the system for a substrate temperature of 400 K [Fig. 2(c)].[11] The microdisk was found to deviate from that of the substrate by no more than 0.14 K, which is much less than the specified thermocouple error of ±2 K; as such, we can assume that T_{disk} is effectively the same as the measured substrate temperature T.

To determine the mode wavelength λ_{res}, the spectrum was fit to a Lorentzian line shape after background subtraction. This method allows a very precise (better than ±0.001 nm) measurement of λ_{res} due to the sharpness of the mode, which possessed a quality factor of $\sim 1.4\times 10^4$ that did not change appreciably with temperature. The small uncertainty in λ_{res} results in a temperature resolution of 0.03 K in this range. Upon heating the microdisk from RT to 500 K, λ_{res} shifted from 1537.6 to 1541.0 nm with a weak quadratic dependence, as shown in Fig. 3(a). The two (interrelated) physical processes which can contribute to this shift in λ_{res} are (1) a change in the microdisk size via thermal expansion

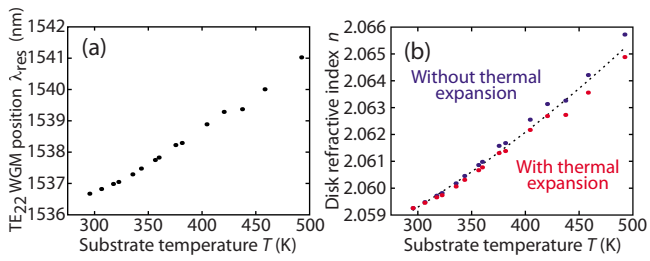

FIG. 3. (Color online) (a) Shift in λ_{res} of the TE_{22} WGM as the substrate is heated. (b) Calculated change in n with temperature; dotted line is a quadratic fit.

and (2) a change in the refractive index via the thermo-optic effect. An estimate for the relative contribution of the former effect can be made using tabulated values for the thermal expansion coefficient α of β-Si_3N_4.[12] In this approximation, heating from RT to 500 K would result in an ~0.04% change in the microdisk diameter, which is not insignificant since the measured change in λ_{res} is only ~0.2%; the majority of the shift in λ_{res}, however, is due to the thermo-optic effect.

To relate the mode position to the microdisk refractive index, we calculated $\lambda_{res}(n)$ using a full-vectorial finite-element mode solver,[2] both with and without including the effect of thermal expansion. First, using the refractive index and disk thickness determined from ellipsometry, we solved for the disk diameter which yielded the RT value of λ_{res} for the TE_{22} mode. For the case of fixed microdisk size, we used $D_{disk}=7.86$ μm, varying n between 2.05 and 2.07; to include thermal expansion, the RT disk height and diameter were multiplied by a factor of $\exp[\int_{T_0}^{T}\alpha(T')dT']$ (α given in Ref. 12) for each temperature value, and n was varied as before. Finally, in either case, the value of n from simulation yielding the experimental value for λ_{res} at each temperature was determined via interpolation to extract $n(T)$. The results of this procedure are summarized in Fig. 3(b). Although the thermal expansion coefficient of a-SiN_x:Er is not known, we may reasonably assume that the refractive index extracted for a fixed disk size represents an upper limit, whereas using the thermal expansion coefficient of β-Si_3N_4 yields a lower limit; a quadratic fit of both data sets simultaneously will therefore yield an estimate for the true value of $n(T)$ [dashed line in Fig. 3(b)],

$$n(T) = 2.0547 + (6.04 \times 10^{-6})T + (3.13 \times 10^{-8})T^2, \quad (1)$$

with T in kelvin. Using this expression and the errors in the coefficients, we find that the TOC changes linearly from 2.4×10^{-5} to 3.7×10^{-5} K^{-1} upon heating from RT to 500 K, with a mean value of $(3.1\pm1.5)\times10^{-5}$ K^{-1}. This thermo-optic behavior is comparable to that of other silicon-based optoelectronic materials such as SiC,[1] and could be used to enable precise thermal tuning of the emission wavelength for microdisk-based extrinsic gain lasers based on this material, or exploited to yield a high-resolution local temperature probe.

In summary, we demonstrate a sensitive method of measuring the thermo-optic effect for light-emitting materials in a useful optical resonator structure by monitoring the center wavelength, upon heating, of a whispering-gallery mode near 1.5 μm in a pedestal-supported a-SiN_x:Er microdisk. In addition to providing a spectroscopic means of tracking the microdisk temperature with a resolution of ~30 mK, this technique yields the thermo-optic coefficient of this attractive photonic material—a necessary quantity for the effective design of electrically pumped, silicon-compatible sources.

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