A Diode Laser Chemical Sensor Utilizing an Oxidized Lower Cladding Layer for High Sensitivity

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Abstract: We demonstrate a novel chemical sensor incorporating a symmetrically-clad high index contrast evanescent field sensing waveguide fabricated with a self-aligned process. An analyte overlap of 4.8% is obtained with a tightly confined mode, ideal for sensitive affinity assays.

Introduction. There is a growing need for biochemical sensors that are sensitive, fast, small, low-powered and inexpensive, for use in medical, industrial, and military applications. A variety of monolithically integrated evanescent field sensors have been demonstrated based on waveguide interferometers or on-chip heterodyne detection [1-3]. It has been shown that for optimal sensitivity to thin chemical layers surface-bound to the sensing waveguide, as used for example in affinity assays, the sensing waveguide must be symmetrically clad, and have tight optical confinement [4]. Symmetrically clad dielectric waveguides have been demonstrated with very high sensitivity for bulk sensing, but due to the small index contrast between core and cladding, Δn, they offer only modest optical confinement. The need for careful alignment between the integrated laser's semiconductor waveguide and the dielectric waveguide also makes fabrication difficult. An all-semiconductor waveguide has also been demonstrated, but the highly asymmetric cladding limited the mode overlap with an analyte to 0.02% [5]. We report here a self-aligned, semiconductor core, quasi-symmetric waveguide sensor providing 4.8% overlap with an analyte in a tightly confined optical mode.

Device. The major obstacle in constructing a symmetric waveguide was incorporating a low index material below the semiconductor core. This was accomplished without using a difficult regrowth or etching process, but rather by oxidizing a 300 nm $Al_{0.98}Ga_{0.02}As$ layer below the core. The laser itself employs an offset quantum well structure, as shown in the epitaxial layer and device structure in Fig. 1. The active region consists of three 8 nm InGaAs wells with 8 nm GaAs barriers. The waveguide core is composed of $Al_{02}Ga_{0.8}As$, 200 nm thick. The reflector structure used in this laser is a three mirror coupled cavity laser. The cleave at the front (gain) end, the etched facet at the interface between the gain and sensing regions, and the etched facet at the interface between the sensing and absorber regions comprise the three mirrors. In operation, the absorber region is grounded so that no light returns from the rear cleaved facet. The net reflectivity is modulated by the resonance in the passive cavity, producing a mode filter whose center wavelength depends on the modal index of refraction in the passive section. This in turn is influenced by the evanescent interaction with the medium surrounding the passive waveguide.

Fabrication began by etching down to the waveguide in the middle region, thereby eliminating the absorbing quantum wells and forming a trench for the sensing region. Next, the ridge was patterned such that the middle region is narrower than the gain and absorber sections. Upon exposing the $Al_{0.98}Ga_{0.02}As$ after etching, a wet oxidation was performed to completely oxidize the sensing region in the middle but not completely oxidize under the gain and absorber sections. Thus, the effective widths of all three sections were relatively the same, 3 μm, providing a single lateral mode. The gain, sense, and absorber sections were 400, 40 and 200 μm long, respectively. The process was finalized with Ti/Pt/Au p-contacts, and AuGe/Ni/Au n-contacts on the thinned backside substrate. The devices were cleaved and mounted onto copper studs for pulsed testing.

Results. For chemical sensing, the entire device was submerged in a temperature-controlled bath of fluid held at 18˚C. To avoid wavelength shifts due to self-heating, the device was tested with 500 ns pulses at a repetition rate of 10 kHz. The gain section was biased at 45 mA, 5 mA above threshold. Five different alcohol mixtures were tested; for clarity, only three of the lasing spectra are shown in Fig 2. An interpolation scheme was used to determine the filter center wavelength from the intensities of the three strongest lasing modes. As shown in Fig. 3, this filter wavelength shifted nearly linearly with the index of refraction of the bathing fluid. The modal overlap with the fluid to be sensed, Γ, is given by the equation,

$$\frac{\Delta\lambda}{\lambda} = \Gamma \frac{\Delta n_{fluid}}{n_{eff}}.$$

This was calculated to be 4.8%, a hundred-fold improvement over previous work with an asymmetric waveguide and in fair agreement with 2D mode simulations of 3.7%, assuming an oxide index of 1.6.

Discussion. While this device, coupled with an inexpensive wavemeter, might be useful as is, the more important result is that a manufacturable technique has been developed to monolithically couple symmetrically clad high index contrast waveguides to conventional semiconductor laser waveguides. Integration of such structures into sensors based on either interferometric or heterodyne detection would yield world-record performance, allowing affinity assays with femtogram sensitivity from picoliter volumes.

References.

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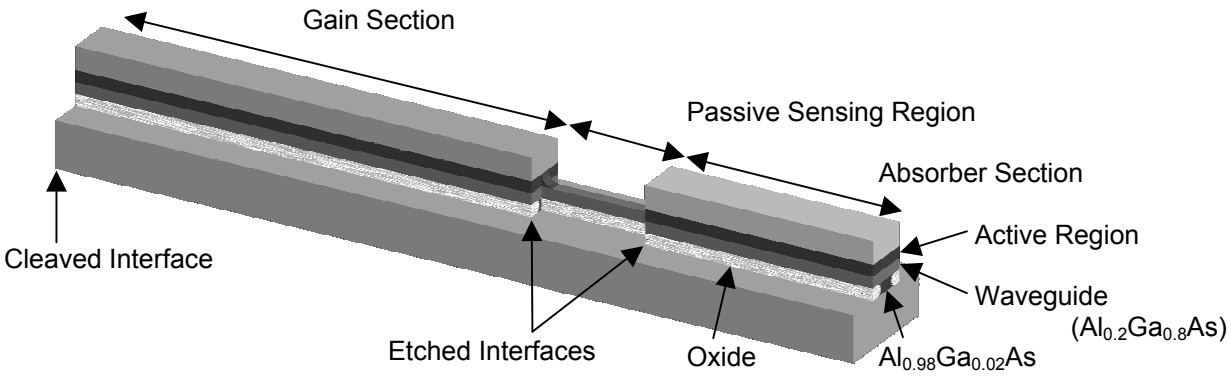

Figure 1. Schematic of the layer and device structure of the coupled cavity laser sensor. Note the narrower ridge width in the sensing region, allowing complete oxidation beneath the waveguide layer to form a quasi-symmetrically clad waveguide.

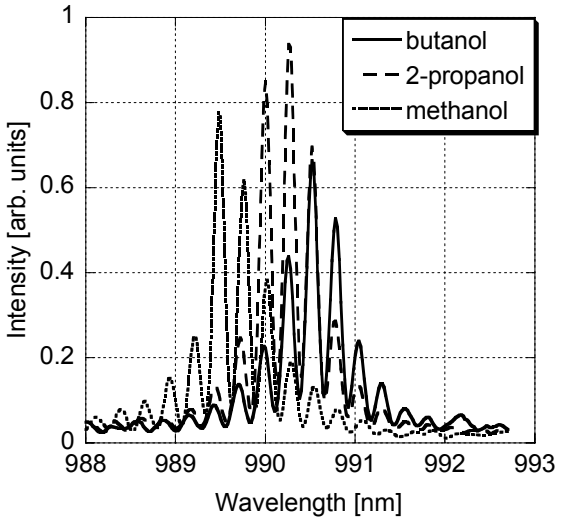

Figure 2. Lasing spectra for three different fluids bathing the sensor. The mode filter center wavelength depends on the fluid index of refraction, and is found by interpolation between the dominant modes.

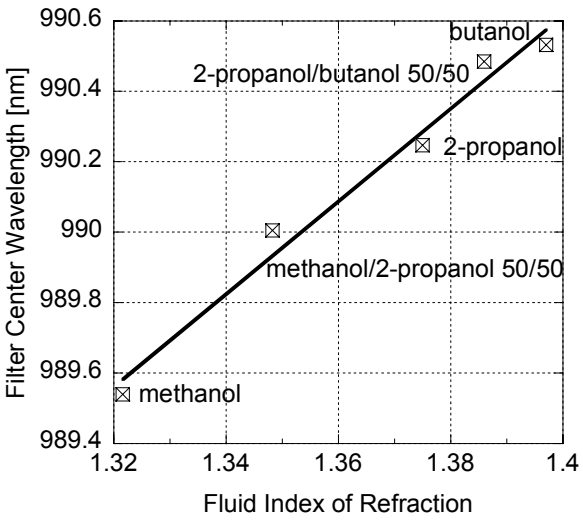

Figure 3. Filter center wavelength as a function of the fluid index of refraction. All fluid indices were measured with an Abbe refractometer.