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Cavity Resonance Tuning of Asymmetric Fabry-Perot MQW Modulators Following Flip-Chip Bonding to Silicon CMOS

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Abstract **– We present a post-integration cavity resonance tuning technique for asymmetric Fabry-Perot MQW modulators flip-chip bonded to silicon CMOS. The process relies on highly selective chemical etching and GaAs surface oxidation. High-quality devices are successfully integrated.**

I. INTRODUCTION

Optical interconnections promise extremely dense, high-bandwidth I/Os onto a CMOS chip, surpassing many of the limitations imposed by common electrical approaches. To achieve this goal, optoelectronic devices are typically fabricated in large arrays and integrated onto completed silicon CMOS. Here we demonstrate a novel technique that allows the performance of entire arrays of devices to be improved after bonding, offering a high-yield process that enables simplified realization of dense optical interconnects to standard CMOS.

Several groups have reported successful integration of VCSELs and MSM photodetectors [1], as well as modulators and photodiodes [2], by flip-chip bonding the devices to active circuitry. Because of the easier growth and device processing, we have chosen to fabricate and flip-chip bond arrays of coplanar-contact multiple-quantum-well (MQW) modulators that can act both as transmitters and detectors.

While the standard double-pass MQW modulator has commonly been used in optical interconnect links, it has been demonstrated that such a modulator can be improved by placing it in a resonant Fabry-Perot cavity [3]. Typically, the active region of such a device is grown with a distributed Bragg reflector (DBR) on one or both sides, producing a low-voltage device with large change in reflectivity and high contrast ratio.

Despite the benefits, the development of integrated asymmetric Fabry-Perot modulators (AFPMs) has been very limited, in large part due to the high accuracy required during growth of the cavity. To obtain a working device with the desired performance enhancement, the cavity resonance must overlap the exciton absorption peak. Such an overlap requires a precise cavity thickness; however, a rather small growth error can cause a shift in the cavity resonance position larger than the exciton peak width [4]. Equally problematic is the thickness variation across a wafer. These two growth errors are typically around a few percent. Our approach to cavity tuning can compensate both growth problems. Another advantage of our device is that no DBR mirrors are required. The cavity uses a metal contact as the bottom mirror and the optically-flat semiconductor/air interface as the top mirror. This design circumvents the problem of growing doped Bragg mirrors with low series resistance.

To achieve the benefits of an AFPM without the strict growth requirements, we use a combination of surface oxidization and selective wet etching to tune the Fabry-Perot cavity following flip-chip integration. Our devices show excellent uniformity across an array, and they can be tuned chip-by-chip as needed. This post-integration compensation of the cavity resonance also allows use of the entire wafer, despite thickness variations from wafer center to edge. Previously, other groups demonstrated post-growth tuning techniques that included: an extra layer deposition step to compensate wafer thickness errors [5], controlled timed etching of the wafer [6], and timed etching of DBR-based devices after fabrication but without bonding [4]. Ours is the first approach that allows cavity tuning of the modulators following integration. It enables us to iteratively test and tune the actual bonded devices rather than the wafer, precisely aligning the Fabry-Perot resonance relative to the exciton peak for each chip.

In this paper, we present the results of our work on the fabrication and tuning of our modulators. We also discuss the integration technique and describe the characteristics of devices bonded to test structures and CMOS circuits.

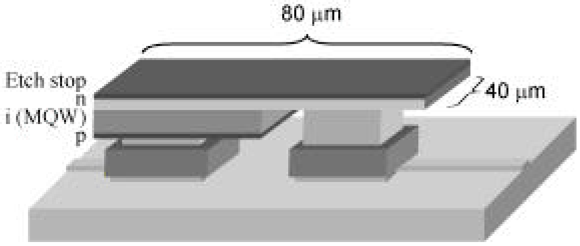

Figure 1. Schematic of device following integration.

II. CAVITY TUNING

As with other previously flip-chip bonded modulators [2], we employ a gold contact as the highly-reflective bottom mirror. However, rather than applying an anti-reflection coating to the devices following integration and substrate removal, we intentionally create a resonant cavity. To achieve a high-quality top mirror, we follow a substrate removal procedure similar to [2], but employ a more selective substrate etch and stop on an $Al_{0.6}Ga_{0.4}As$ etch stop layer. The substrate

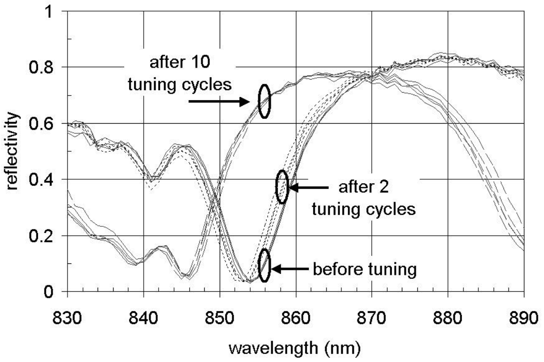

Figure 2. Device reflectivity before tuning, after 2 tuning cycles, and after 10 tuning cycles.

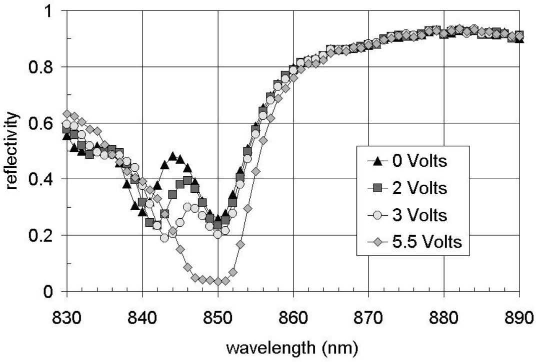

Figure 3. Reflectivity vs. bias for an integrated device, following cavity tuning and epoxy removal.

etch is 4:1 citric acid:hydrogen peroxide, and has an etching selectivity for GaAs over AlAs of greater than 1000:1 [7]. To remove the etch stop layer, we can use hot, concentrated hydrochloric acid, which etches AlGaAs over GaAs with an even higher selectivity than the citric acid etch used for substrate removal [8]. These highly selective etches uncover arrays of devices that are extremely uniform in thickness.

Following etch stop removal, the cavity tuning procedure can be performed. Rather than using a timed etch to thin the cavity, we employ a series of “tuning cycles” that allow precise control of the cavity resonance. A single tuning cycle consists of 30-second dips into hydrogen peroxide and then hydrochloric acid. The process works by oxidizing a thin layer of GaAs and subsequently stripping it off with HCl. The etch depth per tuning cycle has been shown to be very repeatable and around 15 Å. The procedure has an additional benefit: It has been shown to reduce the rms surface roughness to only about 2 Å over areas significantly larger than our arrays [9].

III. DESIGN, FABRICATION, AND INTEGRATION

The devices were fabricated on a wafer grown by solid source molecular beam epitaxy. The epilayer structure consists of a 3000 Å $Al_{0.6}Ga_{0.4}As$ etch stop layer, followed by a 1000 Å GaAs buffer layer that can be etched away during the tuning process. Next is the *p-i-n* diode, comprised of a 4000 Å *n*-$Al_{0.3}Ga_{0.7}As$ layer, a 50-period intrinsic GaAs/$Al_{0.3}Ga_{0.7}As$ (95 Å/35 Å) MQW layer, and finally a 2000 Å *p*-$Al_{0.3}Ga_{0.7}As$ layer with 100 Å *p*+ GaAs cap.

Optical absorption coefficients for the active region of the wafer were determined experimentally, and the data was used to calculate the index of refraction using a Kramers-Kronig transformation approach. Next, the device was simulated using optical transfer matrix methods to determine the expected reflectivity vs. wavelength and applied bias, and the dependence on cavity thickness. Modeling methods and results will be described in greater detail during the talk.

Modulators were fabricated in two-dimensional arrays of 200 devices each, with hundreds of arrays processed in parallel. A six-mask fabrication process was used to create the 80 μm x 40 μm devices and apply the indium solder bumps. In addition to processing the GaAs wafer, the Si CMOS aluminum flip-chip bond pads were metallized with layers of Cr/Ni/Au prior to bonding. Completed device arrays were integrated to CMOS chips, and to silicon test structures with gold bond pads. The bonding was performed on a commercial flip-chip bonder, using a bonding pressure of about 1 gram/contact pad. Following integration, epoxy was wicked between the chips to provide mechanical support and to protect the chip from the subsequent substrate etches described previously. An illustration of an integrated device is shown in figure 1.

IV. TESTING

Testing of the devices was performed on the silicon test structures by optical and electrical probing. After substrate removal, with the protective epoxy still in place (and no modulator bias applied), reflectivity curves were measured using a tunable Ti:sapphire laser. Cavity tuning was then performed to bring the Fabry-Perot resonance to the proper wavelength. Figure 2 illustrates the effects of cavity tuning. The graph shows device reflectivity before tuning and after 2 and 10 tuning cycles. Each set of curves represents data taken from several modulators distributed across the array. Modeling shows that the translation of the resonance peak (about 0.75 nm/tuning cycle) is consistent with an etch depth/cycle of ~20 Å. Also evident in Figure 2 is the uniformity across the array, as seen by the close grouping of all curves within a data set.

Following tuning the epoxy was removed using a CF_4/O_2 plasma, exposing the electrical probe pads. The device reflectivity vs. wavelength was then measured for different applied biases. Figure 3 shows a set of curves for one device at various voltages. Using an offset bias of 3 Volts, we obtain an absolute change in reflectivity (ΔR) of about 20% over 9 nm and a contrast ratio of about 6:1 over 5 nm with a voltage swing of only 2.5 V. Higher voltages give even better performance, with contrast ratios greater than 10:1 and a ΔR around 30% for operation at 0 and 5 Volts.

After the initial devices were tested, additional arrays were integrated to silicon CMOS circuits designed for receiver testing and systems experiments. A scanning electron microscope image of an array bonded directly to silicon CMOS is shown in Figure 4. The CMOS circuits allowed high-speed testing to be performed on the modulators, and Figure 5 shows an eye diagram obtained from a device modulated directly by a CMOS driver at 800 Mb/s.

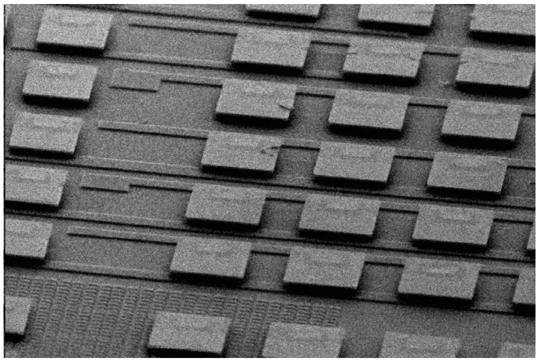

Figure 4. SEM image of a modulator array integrated to a silicon CMOS chip.

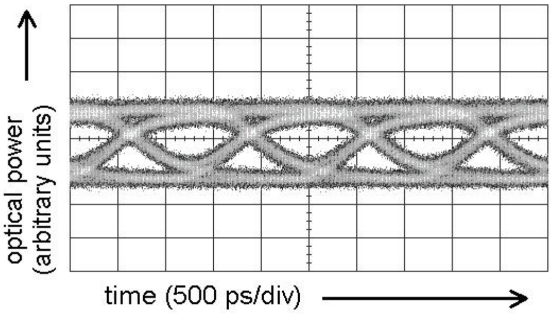

Figure 5. Eye diagram of an integrated device driven directly by a CMOS circuit, transmitting at 800 Mb/s.

V. CONCLUSIONS

Cavity tuning of asymmetric Fabry-Perot MQW modulators has been successfully performed following flip-chip bonding to silicon CMOS. The devices exhibit good performance, and the process has allowed interesting system work to begin. We are currently testing complete chip-to-chip optical links based on the devices described in this paper. We believe that our approach to improving integrated MQW devices, based on highly-selective wet chemical etching and cavity tuning by surface oxidation and oxide removal, is a useful technique that avoids the requirement of extremely high tolerances during growth of low-voltage Fabry-Perot modulators.

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