High-speed all-optical modulation using polycrystalline silicon microring resonators

Kyle Preston, Po Dong, Bradley Schmidt, and Michal Lipson[a)]
School of Electrical and Computer Engineering, Cornell University, Ithaca, New York 14853, USA

(Received 10 January 2008; accepted 24 March 2008; published online 15 April 2008)

We experimentally demonstrate on-chip active photonic devices fabricated from deposited polycrystalline silicon, which can be used for monolithic three-dimensional integration of optical networks. The demonstrated modulator is based on all-optical carrier injection in a micrometer-size resonator and has a modulation depth of 10 dB and a temporal response of 135 ps. Grain boundaries in the polycrystalline silicon (polysilicon) material result in faster electron-hole recombination, enabling a shortened carrier lifetime and a faster optical switching time compared to similar devices based on crystalline silicon. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2908869]

Active silicon photonic devices, which dynamically control the flow of light, have received significant attention for their use in on-chip optical networks. High-speed active silicon photonic modulators and switches rely on the plasma dispersion effect,[1] where a change in carrier concentration causes a change in refractive index. This refractive index change can be utilized in micrometer-length resonators[2,3] or millimeter-length Mach–Zehnder interferometers,[4] and the necessary change in carrier concentration can be introduced either by optical pumping[5,6] or by direct electrical injection and depletion.[2–4] Crystalline silicon has previously been used to demonstrate these all-optical and electro-optic modulators, which normally limits the devices to a single layer.

The fabrication of active modulators and switches in deposited polysilicon would enable the vertical integration of photonic networks with complementary metal-oxide-semiconductor (CMOS) process microelectronics. Passive submicron cross-sectional waveguides and ring resonators have been demonstrated in polysilicon films,[7,8] but active polysilicon devices have yet to be demonstrated. In this letter, we demonstrate a modulator based on deposited polysilicon. The device uses an all-optical scheme to inject free carriers and change the effective index in the structure.[1] We also demonstrate that the carrier lifetime in these polysilicon devices is shorter than in similar crystalline silicon devices.

We fabricate the devices by growing a 2 μm layer of thermal oxide on a silicon wafer and depositing 250 nm of amorphous silicon by low pressure chemical vapor deposition at 550 °C. We then anneal the film at 600 and 1100 °C to crystallize it into polysilicon and minimize optical losses.[7,8] We pattern 450 nm wide devices by e-beam lithography and chlorine-based etching. A fabricated microring resonator is shown in the scanning electron microscope (SEM) image in the inset of Fig. 1 before cladding with oxide by plasma enhanced chemical vapor deposition. A resonance at $\lambda_0 = 1568.28$ nm for the quasi-TM-polarized mode in the through-port spectrum of an oxide-clad 40 μm radius ring resonator is shown in Fig. 1. The full width at half-maximum bandwidth is $\Delta\lambda_{FWHM} = 0.140$ nm, corresponding to a loaded quality factor $Q = \lambda_0/\Delta\lambda = 11\,200$ and a photon lifetime $\tau_{ph} = Q\lambda_0/(2\pi c) = 9.3$ ps. The extinction ratio on resonance is more than 18 dB, indicating near-critical coupling.

We demonstrate all-optical modulation of the device using a pump-probe optical setup. A mode-locked Ti:sapphire laser provides 100 fs pulses of light with an 80 MHz repetition rate at $\lambda = 820$ nm, which we frequency double to $\lambda_{pump} = 410$ nm with a beta barium borate crystal. Pump pulses are focused from above onto the ring resonator, where the light is absorbed to generate free carriers and blueshift the resonance by the free carrier plasma dispersion effect.[1] A quasi-TM polarized continuous-wave probe beam is coupled on and off chip using nanotapers.[9] Time-resolved output from the chip is collected by an objective lens, passed through a polarization filter, collimated into an optical fiber, and sent to a 15 GHz photodetector. A typical measured response is shown in Fig. 2 for $\lambda_{probe} = 1568.12$ nm and a pump pulse arriving at time $t = 0$. The measurable extinction ratio is limited by the relatively slow response of the detector in approximately the first 150 ps. The 10 dB extinction shown in Fig. 2 corresponds to a wavelength shift $\Delta\lambda = 0.14$ nm, or an effective index shift $\Delta n_{eff} = 1.76 \times 10^{-4}$. This is equivalent to a change in the refractive index of silicon $\Delta n_{Si} = 2.06 \times 10^{-4}$ which is caused by a maximum carrier concentration $\Delta N = \Delta P = 4.19 \times 10^{16}$ cm^{-3} generated from the absorbed

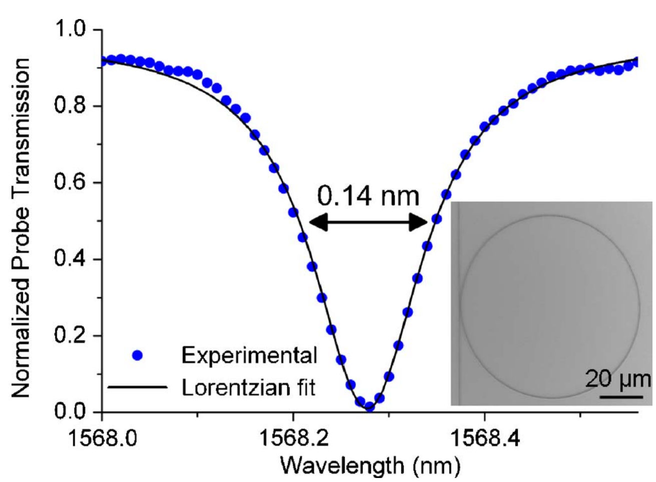

FIG. 1. (Color online) Through-port spectrum of a polysilicon ring resonator in quasi-TM mode. Inset: SEM of polysilicon ring resonator and bus waveguide.

[a)]Electronic mail: ml292@cornell.edu.

0003-6951/2008/92(15)/151104/3/$23.00

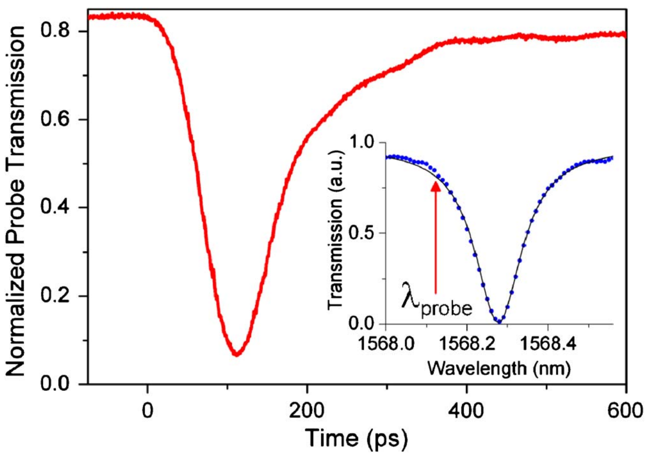

FIG. 2. (Color online) All-optical modulation in a polysilicon ring resonator with a 10 dB modulation depth. Inset: location of the probe wavelength relative to the microring resonant wavelength.

pump light.[1] Given the energy per absorbed photon and the volume of the ring, we estimate that a switching energy of 535 fJ/bit is required for this device to reach a 10 dB modulation depth. The recovery time required from the onset of the pump pulse to return to −1 dB is 250 ps, which is approximately a factor of 3 faster than the recovery time in a similar single-crystalline silicon device.[5,6]

An advantage of the polycrystalline material, in addition to serving as a platform for monolithic three-dimensional (3D) integration, is its lower carrier lifetime when compared to crystalline silicon. This is a critical property in the design of high-speed modulators. A measured exponential decay of the number of free carriers in a device provides an effective carrier lifetime, described as the parallel combination of all the available relaxation pathways

$$\frac{1}{\tau_{\mathrm{eff}}} = \frac{1}{\tau_{\mathrm{bulk}}} + \frac{1}{\tau_{\mathrm{surf}}} + \frac{1}{\tau_{\mathrm{diff}}} + \dots , \qquad (1)$$

where τ_{bulk} is the bulk recombination lifetime for silicon, τ_{surf} is the lifetime for fast recombination at the surfaces of the silicon structure, and τ_{diff} is the lifetime for carriers to diffuse away from the optical mode. Bulk recombination τ_{bulk} in silicon is on the order of 1 μs or more[10] and can be ignored when faster mechanisms are present. Submicron 450 nm wide by 250 nm tall channel waveguides in single crystalline silicon have $\tau_{\mathrm{eff}} = \tau_{\mathrm{surf}} = 450$ ps.[5,6] One approach for lifetime reduction is to physically alter the silicon by ion implantation, which creates defects throughout the material. These defects act both as traps and recombination centers for free carriers (decreasing τ_{eff})[11] and as scattering points for light (increasing optical losses and lowering resonator quality factors). This technique has recently been demonstrated using Ar^+ implantation in a photonic crystal cavity[12] and O^+ implantation in a crystalline silicon ring resonator.[13]

The use of polysilicon decreases the effective carrier lifetime due to an effect similar to carrier annihilation by ion implantation. Polycrystalline silicon consists of regions of crystalline silicon separated by nanometer-thin grain boundaries. This is shown in the transmission electron microscope (TEM) image in Fig. 3 of a polysilicon film before lithography. The disordered boundaries mostly consist of amorphous silicon and typically contain a trap density around mid-10^{12} cm^{-2} of grain boundary area.[14] Grain boundaries

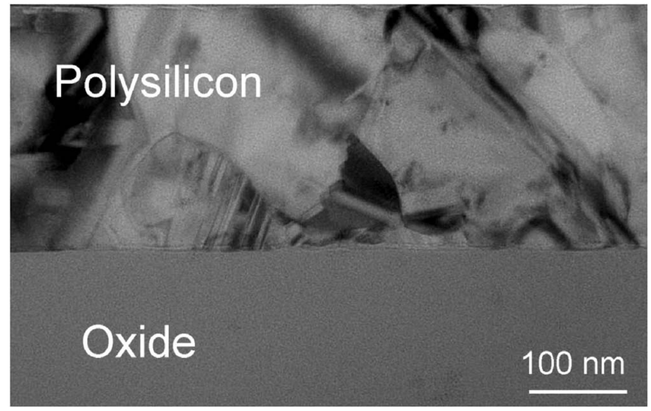

FIG. 3. Cross-sectional TEM image of deposited polysilicon film showing crystalline grains separated by grain boundaries.

and defects within the crystalline grains act as both traps and recombination centers for free carriers.[15] Given a grain size of approximately 300 nm[7,8] and the empirical relation $\tau_{\mathrm{eff,poly}} = 5 \times 10^{-6} \times d$ with d the grain size in centimeters,[15] we would expect a carrier lifetime on the order of 150 ps.

We directly measure the carrier lifetime in our devices by decoupling the carrier response from the resonator's Lorentzian lineshape. To do this, we tune the probe wavelength to the near-linear portion of the resonance ($\lambda_{\mathrm{probe}} \approx 1568.3$ nm) and use small pump energies to perturb the resonance while keeping the probe within the linear regime. The decay tail in Fig. 4 is then linearly related to the recombination of free carriers and the experimental lifetime can be extracted by fitting a simple exponential. Averaged across multiple measurements, we find an effective carrier lifetime $\tau_{\mathrm{eff}} = 135 \pm 5$ ps, which is a 3.3 times reduction as compared to crystalline silicon.[5,6] To further quantify the lifetime reduction, we use the form of Eq. (1) with only $\tau_{\mathrm{surf}} = 450$ ps from the crystalline silicon experiment and an additional relaxation pathway τ_{gb} due to grain boundaries and additional defects within the grains. Using this first-order approximation, we calculate $\tau_{\mathrm{gb}} = (\tau_{\mathrm{eff}}^{-1} - \tau_{\mathrm{surf}}^{-1})^{-1} = (135^{-1} - 450^{-1})^{-1} = 200$ ps. This shows that the additional recombination we have introduced is approximately twice as fast as the pre-existing surface recombination.

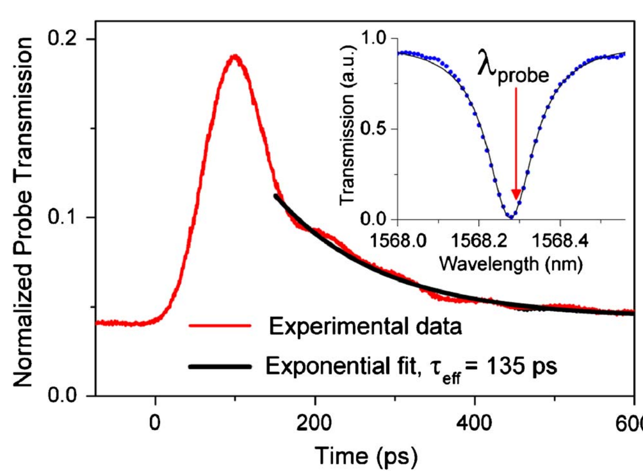

FIG. 4. (Color online) Measurement of effective carrier lifetime using a pump pulse with small energy. Inset: Location of the probe wavelength relative to the microring resonant wavelength.

While decreased carrier lifetime in polysilicon comes at the expense of increased optical losses, we show here that these losses still enable sufficiently high-Q resonators to be used as high-speed, low-switching energy modulators. The tradeoff between speed and optical loss exists because the same grain boundaries and defects that lower the lifetime also cause optical loss by Rayleigh scattering (due to inhomogeneity) and absorption (due to dangling bonds). The increased losses are a challenge for resonator-based all-optical and electro-optic modulators because they increase the energy per bit required to achieve a given modulation depth. Higher losses lead to lower Q factors and broader resonances, meaning that more energy must be put into the resonator to shift by a larger $\Delta\lambda$ and maintain the same modulation depth. While Q values are highly dependent on fabrication conditions, the polysilicon resonator shown here has a Q value of two to three times lower than crystalline silicon resonators fabricated using the same lithography and etching steps.[3] In addition to the achievable resonator quality factor, the loss value is important for the bus waveguides that guide light to and from the modulator. We have demonstrated polysilicon waveguide losses on the order of 10 dB/cm,[8] which is too high for centimeter-length bus waveguides in a practical on-chip network. However, an advantage of working with deposited materials is that active polysilicon devices could be combined with low-loss waveguides of a different material[8] such as silicon nitride or amorphous silicon.

In conclusion, we have demonstrated an all-optical modulator in polysilicon with a high extinction ratio and low power consumption comparable to crystalline silicon but with a shorter free carrier lifetime. While the carriers here were injected using an all-optical scheme, electro-optic modulation could be achieved by embedding a P-I-N junction around the ring resonator.[2,3,14] Polysilicon as a platform for active photonic devices could enable the monolithic 3D integration of photonics on a CMOS compatible chip.

The authors acknowledge support by Intel Corporation and by the Air Force Office of Scientific Research-DOD (AF-AFOSR) under Contract No. 5710002022. This work was performed in part at the Cornell NanoScale Facility, which is supported by the National Science Foundation (Grant ECS-0335765), and at the Center for Nanoscale Systems, supported by the National Science Foundation.

[1]R. Soref and B. Bennett, IEEE J. Quantum Electron. **23**, 123 (1987).
[2]B. Schmidt, Q. Xu, J. Shakya, S. Manipatruni, and M. Lipson, Opt. Express **15**, 3140 (2007).
[3]Q. Xu, S. Manipatruni, B. Schmidt, J. Shakya, and M. Lipson, Opt. Express **15**, 430 (2007).
[4]A. Liu, R. Jones, L. Liao, D. Samara-Rubio, D. Rubin, O. Cohen, R. Nicolaescu, and M. Paniccia, Nature (London) **427**, 615 (2004).
[5]V. R. Almeida, C. A. Barrios, R. R. Panepucci, and M. Lipson, Nature (London) **431**, 1081 (2004).
[6]V. R. Almeida, C. A. Barrios, R. R. Panepucci, M. Lipson, M. A. Foster, D. G. Ouzounov, and A. L. Gaeta, Opt. Lett. **29**, 2867 (2004).
[7]L. Liao, D. R. Lim, A. M. Agarwal, X. Duan, K. K. Lee, and L. C. Kimerling, J. Electron. Mater. **29**, 1380 (2000).
[8]K. Preston, B. Schmidt, and M. Lipson, Opt. Express **15**, 17283 (2007).
[9]V. R. Almeida, R. R. Panepucci, and M. Lipson, Opt. Lett. **28**, 1302 (2003).
[10]R. Claps, V. Raghunathan, D. Dimitropoulos, and B. Jalali, Opt. Express **12**, 2774 (2004).
[11]F. E. Doany, D. Grischkowsky, and C. C. Chi, Appl. Phys. Lett. **50**, 460 (1987).
[12]T. Tanabe, K. Nishiguchi, A. Shinya, E. Kuramochi, H. Inokawa, M. Notomi, K. Yamada, T. Tsuchizawa, T. Watanabe, H. Fukuda, H. Shinojima, and S. Itabashi, Appl. Phys. Lett. **90**, 031115 (2007).
[13]M. Först, J. Niehusmann, T. Plötzing, J. Bolten, T. Wahlbrink, C. Moormann, and H. Kurz, Opt. Lett. **32**, 2046 (2007).
[14]T. Kamins, *Polycrystalline Silicon for Integrated Circuits and Displays*, 2nd ed. (Kluwer, Boston, 1998).
[15]K. G. Amal, F. Charles, and F. Tom, J. Appl. Phys. **51**, 446 (1980).