Hydrogenated silicon films for low-loss resonant reflectors operating in the visible region

Halldor G. Svavarsson and Muhammad Taha Sultan
School of Science and Engineering
Reykjavik University
Reykjavik, Iceland
halldorsv@ru.is

Kyu Jin Lee and Robert Magnusson
Department of Electrical Engineering
University of Texas at Arlington
Arlington, Texas
magnusson@uta.edu,

***Abstract*— Hydrogenation is a widely used method to improve performance of electronic devices made from silicon but much less frequently to improve corresponding optical properties. Here, we study the possible use of hydrogenation to reduce inherent optical loss in silicon. We address enablement of efficient resonance metastructures such as filters, wideband reflectors, and polarizers via successful outcomes of such experimentation. A noticeable reduction in attenuation is observed.**

Keywords—visible-light silicon photonics, hydrogenation, nanostructures, guided-mode resonance, metamaterials, resonant periodic films

I. Introduction

Spectral decomposition and shaping with patterned surfaces with superwavelength periods has been known for more than a century. Simple diffraction gratings with 1D periods that are substantially larger than the wavelengths of the input light produce smooth spectra with modest efficiency as often used in spectroscopy. In contrast, spatially patterned surfaces and films with subwavelength periodicity sustain dramatic resonance effects as input light couples to leaky Bloch-type waveguide modes sustainable in the film [1-6]. Guided-mode resonant subwavelength devices can have 1D or 2D lateral spatial modulation, or periodicity, as the resonance physics is not dependent on the type of periodicity in any fundamental way. The device physics is dominated by the lateral leaky modes driven by evanescent diffraction orders that couple to the lattice and reradiate and interfere to produce the resultant spectra; this is well understood by now. Due to ease of fabrication and spectral characterization, 1D and 2D films are intensely studied; these spatially modulated resonant films are, in recent times, often called photonic crystal slabs, metasurfaces, or metastructures. There is substantial application potential associated with the class of resonant nanostructured surfaces.

II. Silicon Reflector in the Visible Region

Wideband reflectors are among the devices realized via induced guided-mode resonance. Numerous papers have appeared illustrating designed and fabricated high-efficiency GMR reflectors [7-9]. These reflectors operate in high-refractive-index media in spectral regions where the media are approximately lossless. Silicon is a high-quality, economic material that exhibits small loss for wavelengths above 1100 nm. In contrast, in the visible spectral region, silicon has a complex refractive index close to $n_c = n + ik = 4 + i0.04$ near λ=550 nm. Here, we design a resonant reflector to operate across a wide band centered at 550 nm. With reference to Fig. 1, the parameter set

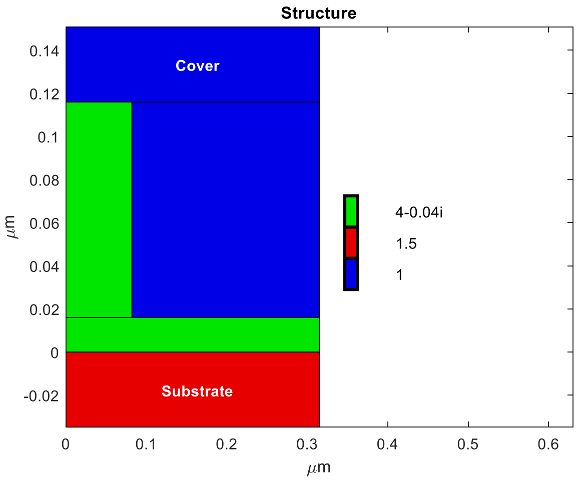

Fig. 1. Schematic of a lossy silicon reflector noting cover medium with index $n_c = 1$, silicon with index $n+ik=4+i0.04$, and substrate with index $n_s = 1.5$.

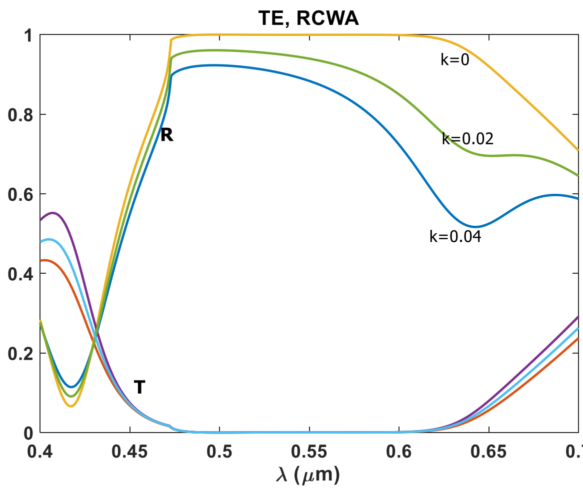

Fig. 2. Computed spectral characteristics of a silicon reflector in the visible region. The group of curves denoting reflectance R having values of k = 0, 0.02, and 0.04.

obtained with particle swarm optimization [10] is period Λ=315 nm, duty cycle F=0.26, grating depth D_g=100 nm and homogeneous sublayer thickness D_h=16 nm. With these parameters, assuming first that k=0, a flat, wide band results with zero-order reflectance R=1, as seen in Fig. 2 (shown for transverse electric (TE) polarized light, using rigorous coupled wave analysis (RCWA)). Taking the native value for k=0.04, there is a significant drop in reflectance as seen in the green curve in Fig. 2. The blue trace corresponds to k=0.02; that is, a loss-reduced silicon film. The zero-order transmittance T is less sensitive to the loss as seen in Fig. 2.

III. Hydrogenation of Silicon Films

It is well established that treatment with hydrogen plasma can passivate deep level traps and defects in semiconductors [11] to a depth of up to several µm [12]. The loss dependency of hydrogenation on thin silicon film was explored with ellipsometry. Physical samples were prepared resulting in a 3.0 µm thick SiO_2 layer on 625 µm thick p-type, 18×18 mm^2 silicon wafer with (100) orientation. The device layer to be hydrogenated is a 0.5 µm Si layer on top of that. A schematic rendition of the structure is given in Fig. 3.

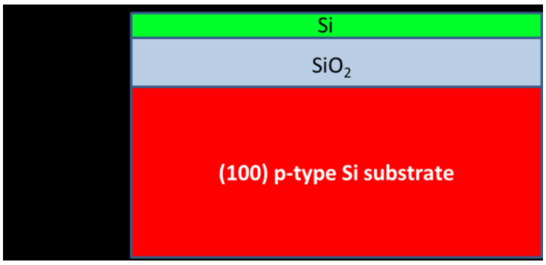

Fig. 3. Schematic of the silicon-on-insulator (SOI) structure prepared for hydrogenation.

The as-fabricated samples were hydrogenated in an inductively coupled radio-frequency (rf) discharge in a cylindrical tube in time spans of 1×10 minutes and up to 7×10 minutes in Ar/H_2 (~70/30 v/v%) mixture with a total pressure of 12 mTorr and applied power of 80 W. During the process, the gas pressure was kept in the range of 0.6–20 mTorr. Radio frequency CESAR© 136 rf power generator (13.56 MHz) source coupled with an impedance matching unit was used to generate the plasma. The highest temperature reached during operation was 48°C as measured by thermal stripes placed inside the hydrogenation chamber. The k-value was measured with an ellipsometer as ~0.02 at λ=550 nm (chosen as the mid point of the visble spectrum). This value is noticably lower than the normally reported value of ~0.04.

IV. Conclusion

In summary, upon exposure of silicon films to low temperature (< 50°C) hydrogen plasma, a drop of the complex attenuation coefficient k from ~0.04 to ~0.02 was obtained. A reduction in the k value improves the reflectance as modeled theoretically in Fig. 2. Further reduction of k would impact prospects for efficient silicon-based reflectors and other resonance devices in the visible region.

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