Porous silicon optical transducers offer versatile platforms for biosensors

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A large surface area with easily modified chemistry makes porous silicon an effective transducer for optical biosensing.

Porous silicon possesses unique features that make it particularly useful in the design of optical biosensors. Chemists discovered these properties unexpectedly in the late fifties when they attempted to polish silicon wafers to form better electrical contacts in the first integrated electronic circuits. They used an electrolyte containing hydrofluoric acid, which left a spongelike nanocrystalline silicon structure on the wafer. This roughened, chemically reactive surface makes the material a versatile substrate for biosensors.

Electrochemical etching is now a standard way to fabricate nanostructured porous silicon. The morphology—and consequently the physical and chemical properties of the surface—can be precisely controlled by varying the composition of the electrolyte, impurities in the silicon, and the density of current used to etch the surface. Computer-controlled production can create silicon films with precise thickness and pore sizes that range from a few nanometers up to microns. Moreover, because the etching process is self-stopping, stacks of multiple layers each with a different porosity can be fabricated in a single run.

The dielectric characteristics of each silicon layer, and in particular its refractive index, $n$, can be modulated between those of crystalline silicon ($n = 3.54$, porosity $= 0$) and air ($n = 1$, porosity $= 100\%$). Surfaces with a variety of optical properties can be realized by alternating high and low porosity layers. Examples include Fabry–Perot interferometers, omnidirectional Bragg reflectors, optical filters based on microcavities, and even complicated quasi-periodic sequences (see Figure 1).

Porous silicon also has features that make it useful for creating biosensors, namely, its high surface area and reactive surface chemistry. Optical sensing relies on changes in the material’s photonic properties such as photoluminescence or reflectance when exposed to gaseous or liquid samples. For sensing to be selective, these interactions must be made specific by chemically or physically modifying the surface. A reactive, hydrogenated, specific surface area on the order of 200–500 m$^2$ cm$^{-3}$ assures effective response to several adsorbates.

Reliability of the biosensor will strongly depend on how simple, homogeneous, and repeatable alterations of the surface can be. Substituting superficial Si–H bonds with Si–C ones guarantees a much more thermodynamically stable surface interface. In Figure 2 we report a scheme to chemically replace surface hydrogen atoms with carbon atoms using the N-hydroxysuccinimide ester of undecenoic acid and UV light.

Demonstrating the ability of porous silicon to optically transduce biochemical interactions is only the first step in creating Continued on next page
an optical biochip based on this nanostructured material. In addition, all processes used to fabricate the sensors must be compatible with their use as biological probes. In order for such devices to be feasible, standard integrated circuit microtechnologies will need to be modified and adapted to preserve the stability of both the optical transducer and the biological components of the sensor.

We design and fabricate resonant optical structures based on porous silicon nanotechnology and integrate them into simple lab-on-a-chip devices. Our work focuses on optical biosensing applications of social interest, such as environmental monitoring and biomedical diagnostics. Figure 3 shows a hybrid porous silicon-glass chip, together with an image of fluorescent bioprobes—labeled single strands of DNA—bonded to the chip.

This design could be used to detect specific DNA sequences in genomics applications. Low-cost porous silicon technology could provide a link between conventional CMOS technology and photonic devices to create so-called smart sensors and biochips. A very strong interdisciplinary approach will be required to resolve remaining technological problems inherent in matching the two technologies.

References

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Figure 2. Chemical alteration of the porous silicon surface under UV irradiation substitutes carbon for hydrogen atoms to create a more stable substrate.

Figure 3. Schematic (left) and photographs (right) of the basic element of a lab-on-a-chip based on a porous silicon optical transducer. DNA strands bound to the chip glow green in the photograph.

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