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Group IV Crystalline Nanomembranes: Materials, Technology, and Potential Applications

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Abstract-**Crystalline nanomembranes of Group IV elements offer a new perspective on potential photonic and optoelectronic structures, including flexible photodetectors, photonic crystals, wave guides, light sources, and oscillators.**

I. INTRODUCTION

Silicon-on-insulator (SOI) (and equivalently germanium on insulator (GOI), and other variations) is the source for a new class of nanostructures, crystalline Group-IV semiconductor nanomembranes, which we generically refer to as silicon nanomembranes (SiNMs). In SOI, a SiO_2 layer is interspersed between a thin, crystalline top Si layer and the bottom Si wafer: the ability to etch this buried oxide selectively creates the membranes. When released from the oxide, this layered structure can form extremely flexible thin nanomembranes, with thicknesses from several 100 nm to less than 10 nm, which can be strain engineered and patterned to create various shapes (including sheets, tubes, spirals, and ribbons), depending on how one defines a pattern before release. [1-2] The opportunity to create nanomembranes exists for many other materials beyond Si and Ge: the only requirement is a release layer, a layer that can be preferentially removed without damaging the material of the membrane. The strain is introduced into membranes by careful heteroepitaxial growth techniques.

The most significant properties that distinguish nanomembranes from bulk Si (or Ge, etc.) are thinness and flexibility, the ability to stack and easily bond different membranes, and the ability to engineer strain into the material, all without destroying the perfect crystallinity. The consequence is a wide variety of potential applications in photonics and optoelectronics, flexible electronics, thermoelectrics, and sensors. We focus here primarily on the potential of nanomembranes for Group IV optoelectronic and photonic applications.

In many of these applications specifically, the enabling technology is membrane transfer. With the several good transfer methods that have been developed, including wet transfer, dry transfer, or transfer printing, [3-5] and the ready adhesion of thin membranes to most any other substrate, it is possible to create many novel structures. Transfer of unstrained Si or Ge nanomembranes released directly from SOI or GOI offers the simplest avenue for making such structures. Such transfer technology has enabled very fast flexible electronics. [5, 6] More recently hemispherical [7] as well as efficient flexible [8] photodetectors, filters [9], photonic crystals, or light sources have been demonstrated or investigated.

II. FLEXIBLE OPTOELECTRONICS

Flexibility is perhaps the most obvious factor allowing new device configurations based on very thin crystalline sheets. A particular recent example is a flexible, curved photodetector based on GOI and the transfer of Ge membranes to a flexible substrate, polyethylene terephthalate (PET).

Ge is ideal for photodetection because it has a very high light absorption coefficient across a larger range of wavelengths than other common materials, as shown in Fig.1. Ge can therefore achieve high photoresponse even as a very thin membrane. The Ge band gap is compatible with optical communication wavelengths of 1.3 and 1.55 μm and absorption is high. Because the hole mobility and low-field drift velocity of Ge are the highest among all types of semiconductors, very fast photodetectors should be possible.

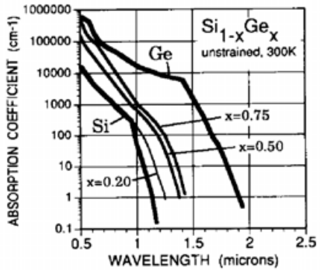

Figure 1. Absorption coefficients of Si and Ge and their alloys.

Figure 2 shows an image of such a flexible photodetector. Single-crystal Ge-membrane photodiodes are monolithically integrated on PET. They can potentially be used for flexible image scanners, sensors, or an artificial retina. Figure 3 show the obtainable quantum efficiency from these devices. [8]

Figure 2. Image of an array of lateral PIN diodes made from Ge nanomembranes to make a flexible photodetector. From Ref. 8.

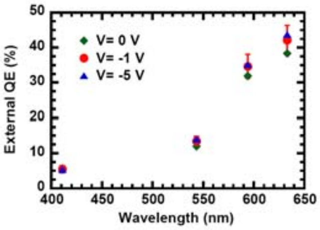

Figure 3. External quantum efficiency of Ge-nanomembrane-based lateral PIN photodiodes as shown in Fig 2. From Ref. 8

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III. PHOTONICS APPLICATIONS

Recent activity in photonics applications using Si nanomembranes has revolved around patterning and transfer of either single sheets or the stacking of multiple sheets to create new function. Surface-normal photonic components (filters, modulators, reflectors, detectors, etc) can be built for 3D photonic integration. In one application, single patterned sheets (a 2D photonic crystal) have been used to create Fano filters. Figure 4 shows the required structure schematically. [9, 10]

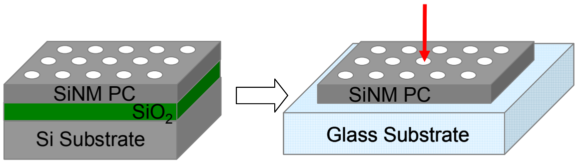

Figure 4. Schematic diagram of a 2D photonic crystal patterned for use in normal-incidence illumination for creating a Fano filter at a specific wavelength, 1550 nm. From Ref. 10.

Figure 5 shows snapshots of field propagation in such structures for both on and off-resonance modes, [10] as determined with three dimensional finite difference time domain simulations. For the on-resonance mode (λ_1), the surface-normal incident light is bounced back from the patterned SiNM structure due to the in-phase reflection, which leads to a dip in transmission. Light off resonance can pass through the patterned SiNM Fano filter with its maximum transmission efficiency.

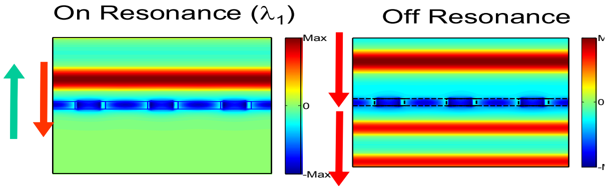

Figure 5. Simulated snapshots of electrical field intensity profiles for on-resonance wavelength (λ_1) and off-resonances, respectively, for structures shown in Fig. 4. From Ref. 10.

With proper membrane transfer and stacking, unique opportunities arise also in fabricating 3D photonic crystals. One approach would be to pattern 2D patterns into individual membranes as above and then align them in the stacking process. Stacking with sufficient precision can be a significant challenge. Quite recently it has been shown that holographic optical tweezers can be used to manipulate nanomembranes, [11] providing a potential future opportunity to align and stack membranes actively. A different approach is to fabricate the photonic crystal by an alternating stack and pattern process, where the alignment precision does not come in the stacking, but in the patterning. Here alignment marks on the template holding the photonic crystal are used to obtain the required precision. The process is shown schematically in Figure 6. A single membrane is first transferred and appropriately patterned. A "blank" membrane is then stacked on top, and using the alignment marks, is subsequently patterned. Figure 7 shows an example.

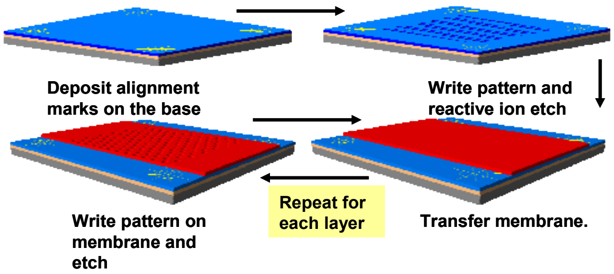

Figure 6. Process design for 3D photonic crystal fabrication using sequential membrane transfer and patterning.

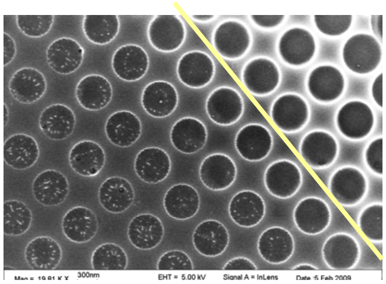

Figure 7. Scanning electron micrograph of a photonic crystal pattern consisting of one layer to the left of the yellow line and two layers to the right. [RB Jacobson, unpublished].

IV. APPLICATIONS BASED ON 3D STRUCTURES

The membranes considered so far are all strain-free. Hence they are in principle flat – or can be made to be flat after transfer. Strain can also be introduced into nanomembranes, and, depending on the desired outcome, can also be made flat, as three-layer sandwiches, or into 3D shapes, such as tubes or corkscrews. Strain introduces band structure changes in Si and Ge, which is of great importance for electronic applications, but the use of strain per se in flat-membrane optoelectronic and photonic applications has not yet been widely explored. Strain can, however, be exploited to make non-flat structures that have or may have unique photonic applications. For example, optically active microtubes have been fabricated by high-temperature annealing of Si/SiOx rolled-up membranes. [12] These tubes form because there is a stress difference in the two layers that cause the layers to roll into 3D shapes when they are released from the handling substrate. Spontaneous emission from such microtubes has been observed and waveguiding along the axis of Si/SiOx tubes has been demonstrated. [12] Figure 8 shows an example.

Finally, strain can be introduced locally into a thin membrane, using nanostressors, such as quantum dots. [13] Such dots can self-organize on both sides of the thin membrane and cause a

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periodic strain lattice. Because strain causes band gap changes the periodic strain can create periodic band offsets, effectively a periodic single-element heterojunction. The result for charge carriers moving thought such a lattice is analogous to charges moving in a Kronig-Penney model of a periodic well. They should therefore radiate. Although simulations on miniband formation in realistic examples of such lattices have been performed, so far we have not made measurements of any potential radiation.

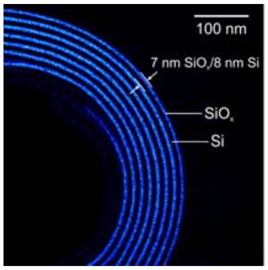

Figure 8. Light emission from a rolled up Si/SiOx bilayer. From Ref. 12.

V. SUMMARY

The use of nanomembranes expands the range of possible uses of Group IV materials in photonics and optoelectronics. Nanomembranes allow new structures, new ways to integrate, new ways to strain engineer, and, in fact, new properties that derive from their nano nature in one or more dimensions. We have described here just a few of the potential applications.

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