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Ultra-thin distributed Bragg reflectors via stacked single-crystal silicon nanomembranes

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In this paper, we report ultra-thin distributed Bragg reflectors (DBRs) via stacked single-crystal silicon (Si) nanomembranes (NMs). Mesh hole-free single-crystal Si NMs were released from a Si-on-insulator substrate and transferred to quartz and Si substrates. Thermal oxidation was applied to the transferred Si NM to form high-quality SiO_2 and thus a Si/SiO_2 pair with uniform and precisely controlled thicknesses. The Si/SiO_2 layers, as smooth as epitaxial grown layers, minimize scattering loss at the interface and in between the layers. As a result, a reflection of 99.8% at the wavelength range from 1350 nm to 1650 nm can be measured from a 2.5-pair DBR on a quartz substrate and 3-pair DBR on a Si substrate with thickness of 0.87 μm and 1.14 μm, respectively. The high reflection, ultra-thin DBRs developed here, which can be applied to almost any devices and materials, holds potential for application in high performance optoelectronic devices and photonics applications. © 2015 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4921055]

Distributed Bragg reflectors (DBRs) are most commonly used as a key component in optoelectronic devices such as photodetectors,[1–4] lasers,[5,6] solar cells,[7,8] and other optical sensors.[9] Typical DBRs consist of quarter wavelength thick multiple layers of alternating materials that have different refractive indices, and the thickness varies from a few to several tens of micrometers, depending on the materials used.[10] There are several parameters that determine the performance of DBRs such as index contrast, layer surface roughness, and interface quality between each layer.[11] High performance DBRs can be formed using epitaxial growth of different materials with similar lattice constants. However, this limits the choice of materials to be used and the corresponding refractive index contrast.[12] Epitaxially grown GaAs/AlAs DBRs, as an example, with a similar lattice constant, are required to have more than 25 pairs, which corresponds to a thickness of 6.2 μm, to achieve >90% reflectivity.[13] A reflection of 99.8% was reported from the GaAs/Al_2O_3 (refractive index: 3.37/1.75) DBRs by forming 4 pairs of GaAs/AlGaAs layers using metal organic chemical deposition (MOCVD), followed by lateral oxidation of AlGaAs to Al_2O_3.[14] However, the starting GaAs/AlGaAs layers can only be grown on lattice matched GaAs substrate, implying that the GaAs/Al_2O_3 DBRs have limited applications. For example, such DBRs are not applicable to 1.55 μm wavelength, for which InP substrate is used. In contrast, Si/SiO_2 DBRs have advantages of low cost and high index contrast of 3.47/1.44 and thus ideally can show >99% reflection with only 3 pairs.

Of more importance, Si/SiO_2 DBRs can be applied to almost any substrate without lattice match limit, as shown below.

Typically, Si/SiO_2 DBRs are fabricated using plasma-enhanced chemical vapor deposition (PECVD) or low-pressure chemical vapor deposition (LPCVD) to deposit polycrystalline or amorphous Si.[1,15] However, the roughness of layer surface increases as more layers are deposited.[16] In addition, non-single crystal material's structural imperfections by the CVD methods degrade the overall DBR performance, thus increasing light scattering.[17] To improve interface roughness and to allow post-epitaxial growth, SIMOX (separation by implanted oxygen) process on single crystal Si substrate was attempted to create DBRs.[11] However, besides the processing complexity and the poor optical performance, the limitation on the choice of thickness of Si and SiO_2 prevents it from achieving ideal design parameters since the interface morphology is critically dependent on the thickness of both layers.[11] Akiyama et al. demonstrated polycrystalline-Si/SiO_2 DBRs via CVD process with a single crystalline top Si layer[16] obtained from a silicon-on-insulator (SOI) (no recycling of the substrate). Due to the use of polycrystalline Si, 7 pairs of Si/SiO_2 were needed to achieve more than 99% reflection. DBR using the ion cut process was proposed to insert single crystalline Si in each pair.[10] Although this method is expected to provide good interface quality and thickness uniformity, multiple steps of ion cut and wafer bonding/polishing prove it to be a cost ineffective method besides the poor reflectivity (90%). It is suggested by Peng et al. that single crystalline Si/amorphous SiO_2 DBRs by the Si layer transfer method and spin-on-glass (SOG) oxide can be used as a low index material.[18] However, the difficulty to precisely control the thickness of the oxide layer using the SOG process severely degrades the reflectivity. In addition, the non-uniform SOG oxide surface

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leaves voids at the Si/SiO$_2$ interface after transferring the Si layer, and these voids may affect the DBR performance and the bonding strength between layers.

In this work, we report the demonstration of high reflectivity and ultra-thin Si/SiO$_2$ DBRs using single crystal Si nanomembrane (NM) transfer stacking method without use of any adhesion layer in between each layer.[19,20] The DBR consists of single crystalline Si NM in every Si layer as well as high-quality thermally grown SiO$_2$ layer. The use of such high quality layers enables the development of precisely controllable and uniform layer thickness and allows for very smooth interfaces, as smooth as epitaxial grown layer, which minimize scattering loss at the interface and in the layers and thus lead to the most thin format of DBRs. In addition, the process involved is much simpler than the previously demonstrated Si/SiO$_2$ DBRs.[10,11,16,18]

In order to obtain layer parameters for the best DBR reflection, the simulation was carried out with MEEP (MIT Electromagnetic Equation Propagation).[21] A 110 nm/270 nm of Si NM/SiO$_2$ layer thickness is used and more than 99% reflection is expected from 2.5-pairs DBR on a quartz substrate and 3-pairs DBRs on a Si substrate. Figures 1(b)–1(f) show the illustration of the fabrication process for Si NM/SiO$_2$ DBRs on a quartz substrate. Fabrication starts with thinning down the top Si layer (340 nm) of SOI wafer from SOITEC, with buried oxide (BOX) of 2000 nm, down to 234 nm using thermal oxidation and hydrofluoric acid (HF, 49%) wet etching. The SOI sample was immersed in HF solution to undercut the BOX as shown in Figures 1(a1)–1(a3). The maximum lateral etching distance that allows Si NM to be released without etching holes largely depends on the thickness of the BOX layer. In this experiment, the SOI wafer with a 2000 nm thick BOX layer enables to obtain large Si NMs without etching holes. After releasing the top Si layer, top Si layer with size about 1 mm^2 without etching holes is gently released and rinsed with DI water. Then, Si NM is transferred with a polydimethylsiloxane (PDMS) stamp to the host substrates, i.e., quartz and a Si substrate

without an adhesive layer by a kinetic control of adhesion between a PDMS stamp and Si NM.[19] For the Si substrate, 270 nm thermal oxide is grown prior to Si NM transfer. The detailed procedure about Si NM transfer can be found elsewhere.[22,23] After Si NM transfer is completed on each host substrate, the wet oxidation process is carried out at 1050 °C to grow 270 nm SiO$_2$. It should be noted that 124 nm of the Si layer in Si NM is consumed during wet oxidation. Thus, the final Si/SiO$_2$ layer thicknesses of 110 nm and 270 nm, respectively, were realized following our simulation results. The transferred Si NM is bonded completely during the oxidation process. Following this, other Si NM/SiO$_2$ layers (remarked as the first and the top layers in Figure 1(g)) which are smaller than the second Si NM/SiO$_2$ layer are transferred on top of the oxidized surface and repeated as shown in Figures 1(b)–1(f). In order to stack the Si NMs, a XYZ-axis manipulator is used to precisely locate the subsequent Si NM layer on top of the Si NM/SiO$_2$ layer. Shown in Figures 1(g) and 1(h) are the optical microscope image of a 1 mm^2 sized Si/SiO$_2$ DBR transferred to a quartz substrate and the cross-sectional scanning electron microscope (SEM) image, respectively. Based on the images shown in Figures 1(g) and 1(h), high quality Si/SiO$_2$ DBRs are formed with precisely controlled thicknesses and high quality bonding interfaces. Such high quality transfer of large-area single crystalline Si NM is also essential for high reflectivity DBRs on a quartz or Si host substrate. Reflection spectra were taken using a custom built reflection measurement system with connection to the Fourier transform infrared spectroscopy (FTIR) system at room temperature.

The simulated and measured reflection spectra for 1-pair, 2-pairs, and 3-pairs Si/SiO$_2$ DBRs on Si substrate are shown in Figure 2. The measured spectra agree well with the simulated spectra, which suggest that each Si and SiO$_2$ layer shows the material characteristics close to the simulation. Although the substrates with high refractive index were used, the high reflection, as high as 99.7% at 1550 nm wavelength with the bandwidth of ~270 nm, from 1400 to 1670 nm wavelength,
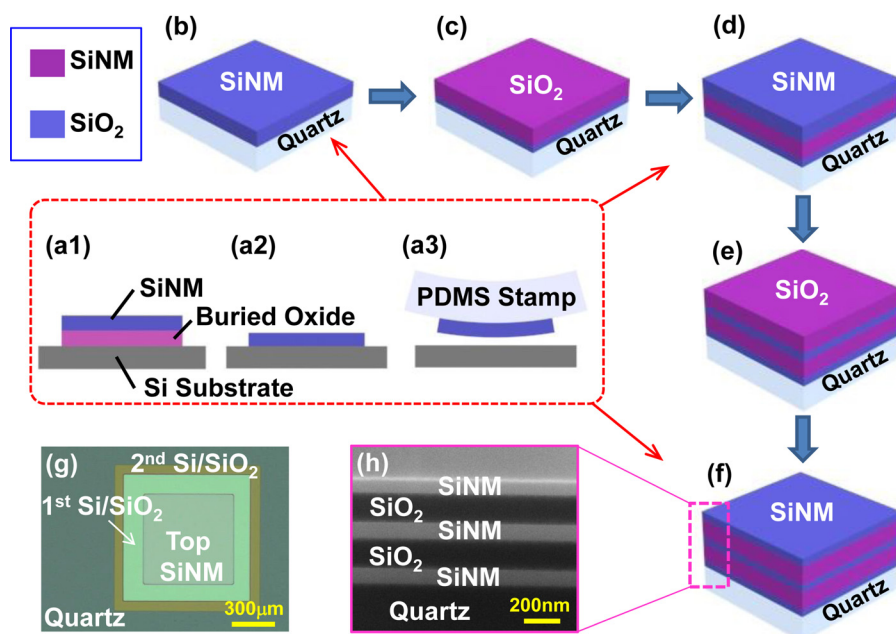

FIG. 1. Images and illustrations of fabrication process for 2.5 pairs Si/SiO$_2$ DBRs on a quartz substrate. (a1)—Patterning of Si NM on SOI, (a2)—separation of Si NM after removal of buried oxide layer, and (a3)—transfer Si NM with PDMS stamp, (b) 1st Si NM transferred onto a quartz substrate, (c) thermal oxidation after 1st Si NM transfer, (d) 2nd Si NM transferred on top of 1st pair, (e) thermal oxidation after 2nd Si NM transfer, (f) 3rd Si NM transferred on top of 2nd pair. (g) A SEM cross-sectional image and (h) an optical microscope image.
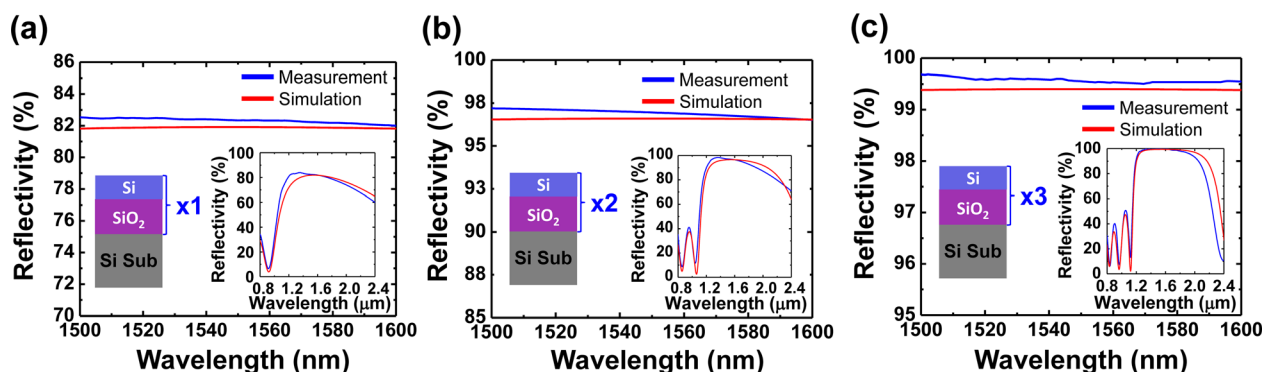
FIG. 2. Measured (blue) and simulated (red) DBR reflection spectra on Si substrates in the range of 1500 nm–1600 nm. (a) 1-pair single-crystalline Si NM/SiO$_2$ DBR, (b) 2-pairs single-crystalline Si NM/SiO$_2$ DBR, and (c) 3-pairs single-crystalline Si NM/SiO$_2$ DBR. Insets show the reflections in a wider wavelength range of 800 nm–2400 nm.
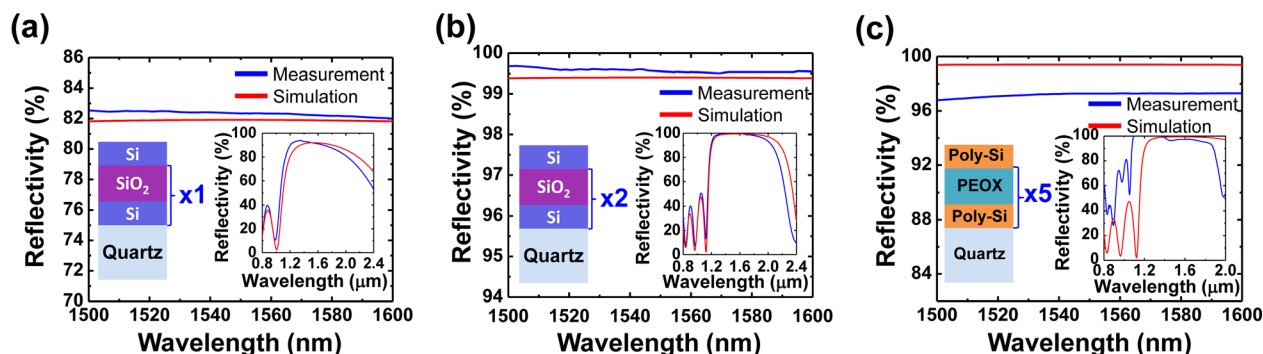

FIG. 3. Measured (blue) and simulated (red) DBR reflection spectra on quartz substrates in the range of 1500 nm–1600 nm. (a) 1.5-pair single crystal Si NM/SiO$_2$ DBR, (b) 2.5-pairs single crystal Si NM/SiO$_2$ DBR. (c) 5.5-pairs polycrystalline-Si NM/SiO$_2$ DBR as a comparison to samples shown in (a) and (b). Insets show the reflections in a wider wavelength range from 800 nm to 2400 nm.

can be achieved after stacking 3 pairs of Si/SiO$_2$ on Si substrate with a total DBR thickness of 1.14 μm.

The Si NM stacking method can be applied to other substrate without limit. To demonstrate the wider applicability of the method, we further fabricated Si NM/SiO$_2$ DBRs on quartz substrates using the same method for the DBRs on Si substrate. Figures 3(a) and 3(b) show the measured and simulated reflection spectra. A half pair is added for DBRs on a quartz substrates, because the initial DBR layer starts with 110 nm thick Si NM. The measured spectra again agree well with the simulated results and show less deviation from the simulated reflection spectra. The total thickness of the 2.5-pairs DBR on quartz is only 0.87 μm. The highest reflection, as high as 99.8% at 1550 nm wavelength with the bandwidth of 400 nm from 1300 to 1700 nm, has been achieved. Our demonstration is the thinnest DBRs along with the highest reflectivity among all published DBRs. Besides that the Si NM/SiO$_2$-based DBRs offer flat and non-patterned surface and are thus mechanically more robust, the result is comparable to the best reflection from Si-membrane reflector (Si-MR), in terms of layer thickness and reflection, while having a wider bandwidth.[24] Such high reflection and wide bandwidth indicate that uniform, high quality single-crystal Si NMs, and the highest quality SiO$_2$ were implemented.

To compare the optical reflectivity of Si NM/thermally grown SiO$_2$ DBRs with DBRs by the CVD deposition method, we prepared multi-pair polycrystalline-Si/PECVD SiO$_2$ DBRs on quartz substrate. The polycrystalline-Si layers

were deposited by LPCVD under vacuum at 700 °C and the SiO$_2$ layers were deposited by PECVD at 350 °C. As shown in Figure 3(c), although the simulation indicates the reflection being >99%, but the measured reflection of this type of DBR only can reach to ~97% after depositing 5.5-pairs polycrystalline-Si/SiO$_2$ layers due to crystal imperfection. Thus, 3–4 more pairs are needed to achieve 99% or higher reflection. This, in turn, proves transfer-stacked Si NM/SiO$_2$ DBR, several folds thinner than the one by PECVD, has low scattering loss.

In summary, the thinnest and the highest reflectivity DBRs were demonstrated by using a simple Si NM transfer stacking method and Si NM thermal oxidation. DBRs with different pairs were fabricated both on Si and quartz substrates, and the simulated and measured reflections are compared. Reflections of 99.8% at the wavelength range from 1350 nm to 1650 nm can be measured from both 2.5-pairs DBRs on quartz substrate and 3-pairs DBRs on Si substrate with a total thickness of 0.87 μm and 1.14 μm, respectively. The highly reflective, ultra-thin, and simple DBRs show potential for thin Si-based optoelectronic devices and photonic applications.

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