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High quality SiC microdisk resonators fabricated from monolithic epilayer wafers

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The exquisite mechanical properties of SiC have made it an important industrial material with applications in microelectromechanical devices and high power electronics. Recently, the optical properties of SiC have garnered attention for applications in photonics, quantum information, and spintronics. This work demonstrates the fabrication of microdisks formed from a p-N SiC epilayer material. The microdisk cavities fabricated from the SiC epilayer material exhibit quality factors of as high as 9200 and the approach is easily adaptable to the fabrication of SiC-based photonic crystals and other photonic and optomechanical devices. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4863932]

The interface between spin physics and nanophotonics has drawn much attention for new platforms in quantum information processing and communications. Much like the Nitrogen-vacancy (NV) center in diamond, defect centers in silicon carbide (SiC) have recently been identified as compelling candidates for applications in spintronics[1] and quantum information science.[2] Several defect spin states have been optically addressed and modulated in both 4H- and 6H-SiC, at temperatures ranging from 20 K to room temperature.[1] The availability of high quality micro-scale and nanoscale optical resonators tuned to the emission frequency of the SiC defect can amplify the impact of these findings. In previous work, we established that the optical efficiency and spin coherence of point defect emitters are particularly sensitive to the quality of the surrounding material, the presence of other structural defects in the material, and any damage incurred through the fabrication process.[3] Thus, the current work focuses on the fabrication of SiC microdisk resonators formed from monolithic SiC, using a low-damage selective photoelectrochemical (PEC) wet etch process. Our initial resonators demonstrate quality factors approaching 10 000.

The approach employed in this work involves a photo-driven dopant-selective wet chemical etch process that can be applied to heterostructures of 4H, 6H, or 3C SiC grown on SiC wafers. Selective etching of n-SiC over p-SiC had been previously demonstrated for both 3C and 6H SiC, using UV illumination of the sample in HF solutions.[4,5] For a given electrolyte, and samples under direct illumination, the higher etch rate of n-type to p-type material is a general feature of photoelectrochemical etch processes,[6] pertaining to semiconductors such as GaAs, InP, and GaN. More recently, related PEC processes have been employed for the fabrication of microelectromechanical systems (MEMs) from SiC, using alkaline solutions, such as KOH.[7,8] Since we routinely employ SiO_2 as a masking material for our devices, we chose to use a KOH-based, rather than HF-based process. The guiding principle of PEC etching is the photo-enhanced formation of holes, which promotes the oxidation and subsequent dissolution of the illuminated material. We chose to pursue this fabrication approach for its compatibility with single-crystal SiC substrates and because the optical isolation of the cavity is then enabled through a low-damage, wet-etch process.

The material employed in this work was p-type SiC epitaxially grown layers on an n^+ SiC substrate (nitrogen--doped, $\sim 1 \times 10^{19}$ cm^{-3}, epilayer supplied by Norstel AB). The high doping of the substrate creates a low-resistance path for the local cathode on the structure, allowing the efficient extraction of photo-created electrons. This latter fact is important for the most efficient use of the photo-generated holes in the etch process. The p-SiC layer was Al-doped, 1×10^{17} cm^{13}, and 250 nm thick. The sample was diced into 6 mm square pieces and a 100 nm thick layer of nickel was deposited on the n-type side to provide an electrical contact (local cathode) for PEC etching. The samples were annealed *in vacuo* at 900 °C for 1 h to create an ohmic contact with the SiC. To define microdisk devices on the p-type epilayer, 3 μm diameter alumina microspheres (Corpuscular) were dispersed onto the SiC surface. Next, the pattern produced by the alumina beads was transferred to the SiC by inductively coupled plasma reactive ion etching (ICP-RIE) in an SF_6/O_2 (40/10 sccm) ambient at 5 mT pressure, 400 W ICP power, and 75 W platen power. The samples were etched for 5 min giving a total etched depth of about 1200 nm. To selectively PEC etch the n-type material and under-cut the p-type layer, the specimens were placed in 0.2 M KOH and illuminated through a 10× microscope objective with a 120 W Hg lamp filtered to remove light with wavelengths longer than 500 nm. Specimens were etched for 15 h with a positive bias of 0.2 V applied between the specimen and a coiled platinum wire anode. A schematic of the device fabrication process is shown in Figure 1(a). A resulting undercut microdisk is depicted in Figure 1(b) with its lateral and vertical etched dimensions labeled "L" and "V," respectively.

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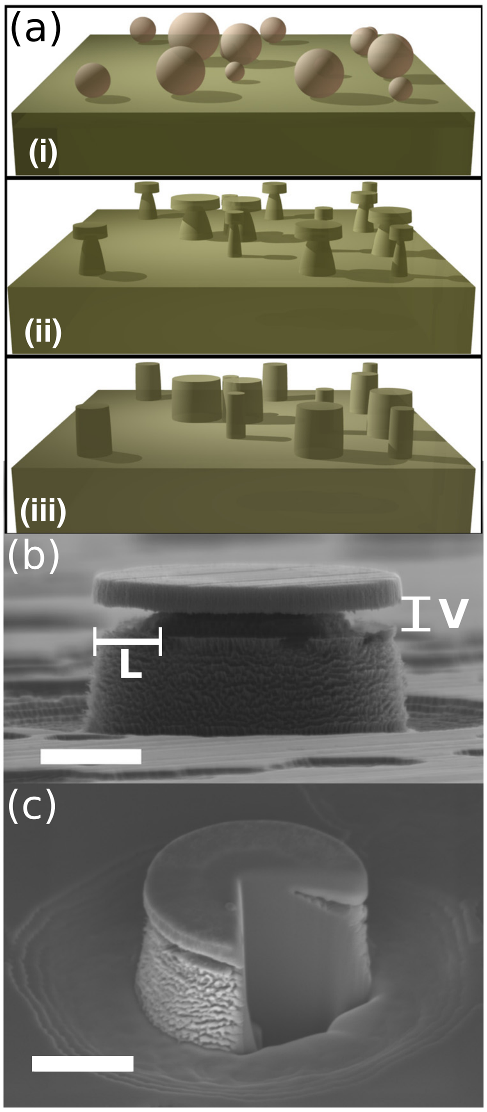

FIG. 1. (a) A schematic of the device fabrication process. Alumina microspheres are dispersed on the SiC surface (i) to act as masks for RIE. RIE creates SiC pillars (ii), which are then undercut using PEC etching to produce microdisks (iii). (b) A well undercut disk after PEC etching with lateral undercut (L) and vertical undercut (V). The scale bar is 1 μm. (c) An FIB cross section of an undercut microdisk showing that the porosity is a surface phenomenon and does not penetrate into the pillar. The scale bar is 1 μm.

Some distinctive features of this undercut etch process should be noted and further explored. Our experience in PEC etching of other materials, such as GaAs or GaN, led us to expect a more uniform and complete removal of the n-SiC, rather than the well-defined layer, marked V in Figure 1(b). One reason for the etch profile obtained may be explained by the band-structure of the particular p-n+ material that was used, with the p-n+ junction together with the water/p-type SiC interface creating a local well for holes, concentrating them close to the p-type layer and augmenting etching in this region. Moreover, the outer periphery of the n-SiC pillar appears porous in nature as seen in Figure 1(c). The formation of porous SiC in a UV-assisted HF-based etch process has been reported by Shor *et al.*[9] A cross-section of the microdisk formed by Focused Ion Beam (FIB) etching reveals that the porosity is confined to the surface of the pillar, as shown in Figure 1(c). However, the additional surface area of the porous surface together with its larger electrical resistance serves to limit the lateral etch rate of the n-SiC pillar. As seen in Figure 2(b), smaller-diameter disks are more effectively undercut than the larger-diameter disks. The SEM micrograph shows two disks of different diameters that were found in close proximity on the same substrate. Statistics for the undercut relative to disk diameter for over 100 disks are shown for the lateral (L) and vertical (V) undercut in Figure 2(c). The lateral undercut nearly disappears for large disks, while the height of the undercut reaches a limiting value of about 0.15 μm.

The optical properties of the microdisks were characterized using photoluminescence (PL) spectroscopy at room temperature. The microdisks were excited using 532 nm laser excitation in a confocal Raman microscope (LabRAM ARAMIS, Horiba Jobin-Yvon). The undercut p-type epilayer exhibited relatively weak broadband PL centered at about 700 nm, similar to the fluorescence signature of silicon vacancies in SiO_2. On well-undercut microdisks, the luminescence is decorated with whispering gallery modes having

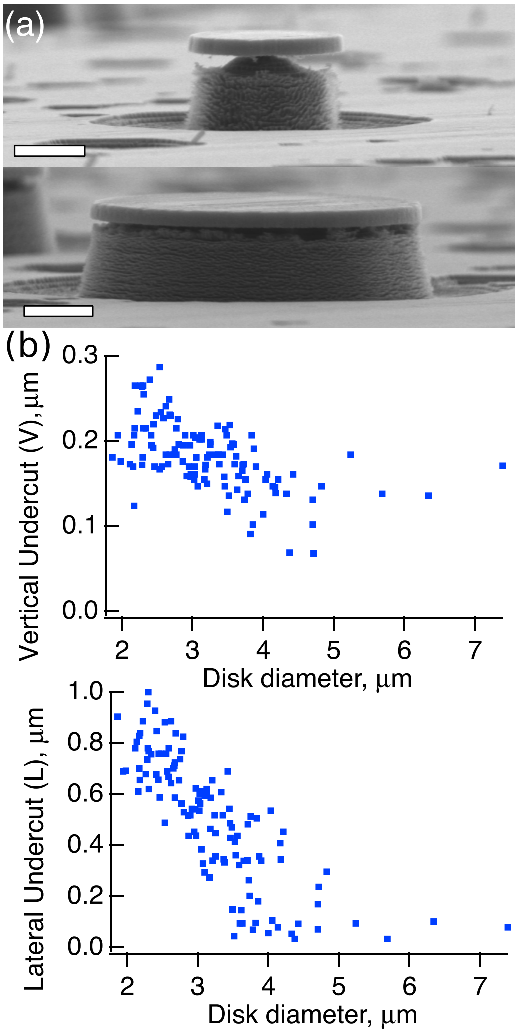

FIG. 2. (a) SEM micrographs of two SiC microdisks. Scale bars are both 1 μm The images show that after PEC etching, the smaller disk (top) exhibits a significantly better undercut than the larger disk (bottom). (c) Microdisk undercut statistics for 120 microdisks from a single PEC experiment. SEM images were used to measure the lateral undercut (top) and undercut height (bottom). These plots clearly show a significant decrease in PEC etching with increased disk diameter.

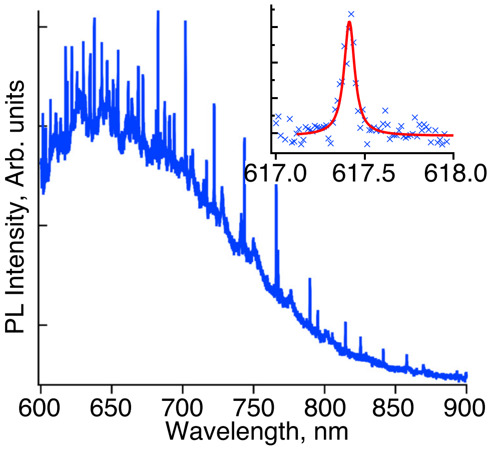

FIG. 3. Whispering gallery modes from a small SiC microdisk (~2 μm) exhibiting a good undercut after PEC etching. This disk exhibits modes having quality factors as high as 9200 (inset).

quality factors measuring at least 9200, shown in Figure 3, approaching the resolution limit of our spectrometer. Larger microdisks with poorer undercuts, and hence poorer optical isolation, had significantly lower quality factors. Finite difference time domain (FDTD) simulations (Lumerical) of a 2 μm diameter disk, separated by 250 nm from a SiC substrate, predicted a maximum Q value of 18 000, on the same order as the experimentally obtained value. Simulations of a fully undercut disk predicted a maximal Q of over 10^5 suggesting that leakage into the pillar is a primary loss mechanism for our structures. We are still understanding how to optimize the PEC etch, but note that the observed lateral undercut is sufficient to form fully-isolated photonic nanobridges or similar structures having small lateral dimensions.

Other approaches to forming SiC photonic structures have either employed SiC grown on non-lattice-matched substrates[10,11] or achieve optical isolation of all-SiC structures using an ion-slicing approach.[12,13] Our approach, using epilayer wafers together with a facile, low-damage PEC process enables the fabrication of SiC photonic devices having quality factors approaching 10 000. With improvements to the surface quality of the epilayer and further optimization of the PEC etch process, devices with even higher quality factors should be possible. Furthermore, this approach is amenable to the fabrication of many optically isolated photonic structures including photonic crystal cavities and nanobeam resonators. Coupling SiC spin centers to such photonic devices will enable further investigations at the interface between spin physics and cavity quantum electrodynamics, thus enabling important new devices for spintronics and quantum information.

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