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# Photoelectrochemical etching to fabricate single-crystal SiC MEMS for harsh environments

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ABSTRACT

In this paper, we report on a novel surface micromachining process technology for the fabrication of microelectromechanical systems in SiC. Single-crystal SiC suspended microstructures were fabricated using a dopant-selective photoelectrochemical etching process, which allows for undercutting the p-SiC layer by rapid lateral etching of the underlying n-SiC substrate. The selective etching was achieved by applying a bias which employs the different flat-band potentials of n-SiC and p-SiC in the KOH solution. Single-crystal SiC MEMS developed in this study fully exploits the superior mechanical and biocompatible properties of SiC and has the capability of monolithic integration with electron devices and circuits, and therefore, is promising for sensing and actuating operations in biomedical, high-temperature and harsh environments.



## 1. Introduction

Si has been the dominant material for microelectromechanical systems (MEMS) due to a variety of advantages, especially the capability of integration with the existing Si-based devices and circuits, and the ease of surface and bulk micromachining compared to other materials. However, Si MEMS found limitations with the increasing attention drawn to operate their structures in extreme environments, e.g., in acids, bases, biological domains, and high temperature (close to 1000 °C) in many industrial and military applications, etc. Si is susceptible to a corrosive medium and exhibits a low biocompatibility, and Si MEMS structures lose the mechanical reliability at 500 °C while Si p–n junctions degrade above 200 °C. A material of choice is SiC, since it offers superior mechanical, thermal, chemical, and biochemical properties [1,2]. SiC is a wide bandgap semiconductor with a $>10^{17}$ times lower intrinsic carrier concentration and >2 times higher thermal conductivity than Si [3], which makes SiC capable of being operated in a temperature range of 600–1000 °C. SiC has a Young's modulus higher than steel, enabling resonant devices to achieve higher frequencies and quality factors. SiC is resistant to mechanical wear and almost all chemicals (except molten KOH above 600 °C), inert to environmental conditions, and shows no or very low surface oxidation at room temperature. All these advantages favor the fabrication of MEMS gas and chemical sensors with simplified system design and packaging. Furthermore, SiC is biocompatible with optimal tribological properties, which makes SiC MEMS suitable for biosensing. Therefore, SiC is promising to challenge Si and enable MEMS technology for applications in harsh environments.

However, the fabrication of SiC MEMS structures has been a challenging task due to the chemical resistance of SiC, since conventional wet chemical etching of SiC is not possible at a practical temperature and with suitable etch rates. In the past, several techniques have been developed to fabricate SiC MEMS. Polycrystalline SiC films [4] or heteroepitaxial 3C-SiC films [5] were deposited on the Si or SOI substrate, or on a sacrificial layer such as $SiO_2$ or poly-Si, with suspended structures released by surface machining using either wet [6] or dry [7] etching process. 6H-SiC strain sensors with “comb fingers” were fabricated by wafer bonding and “smart-cut” technique [8]. Suspended 6H-SiC cantilever beams were demonstrated by employing an anisotropic electron cyclotron resonance (ECR) etching technique [9] from three different angles relative to the wafer surface, or by bulk micromachining [10] from the backside of the wafer using inductively coupled plasma reactive ion etching (ICP-RIE) to etch through the substrate in order to release the cantilever structures patterned on the front side.

In this paper, we report a novel surface micromachining technique — dopant-selective photoelectrochemical (PEC) etching to fabricate single-crystal SiC MEMS structures on an n-type SiC substrate. This technique is well controllable and does not require etching through the SiC substrate, therefore significantly simplifies the fabrication process. Since the substrate and MEMS structures are all single-crystal materials, electron devices and circuits can be fabricated on the same chip and integrated with the suspended microstructures for signal control and

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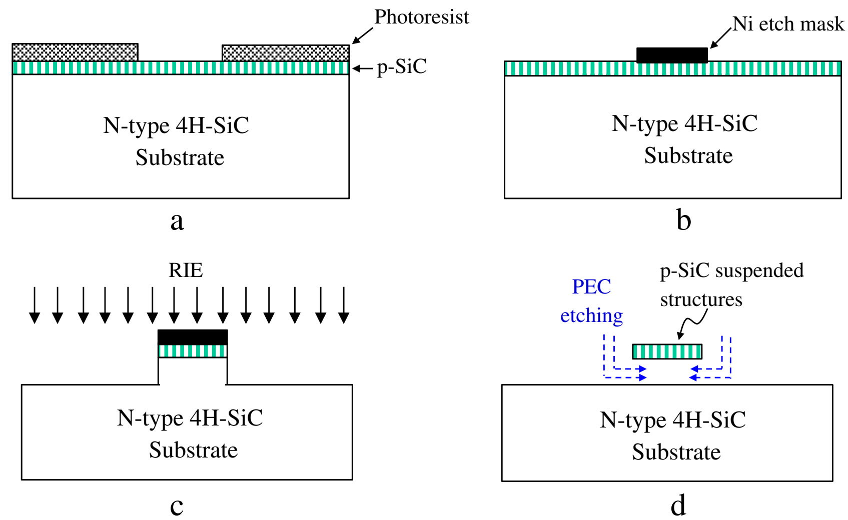


**Fig. 1.** Schematic of the single-crystal SiC MEMS fabrication process: (a) starting material with p-SiC on the n-SiC substrate; (b) photolithography and Ni mask lift-off; (c) RIE etching; and (d) PEC etching with p-SiC MEMS structures released.

amplification. This provides single-crystal SiC MEMS with superior monolithic integration and high-temperature operation capabilities. The elimination of Si and SOI substrates fully exploits the outstanding properties, including mechanical-durability, biocompatibility, high-temperature operation, and high sensitivity of SiC MEMS.

## 2. Fabrication

The process flow is shown in Fig.1. The starting material used for MEMS fabrication is a single-crystal n-type 4H-SiC substrate with a p-type SiC layer on the top (Fig. 1(a)). The p-type SiC can be formed by either epitaxial growth or ion-implantation, which defines the thickness of the final SiC MEMS structures. In this study, a layer of 300 nm p-SiC was grown by CVD. Optical photolithography was performed to define the lateral layout and geometry (width and length, or diameter) of the MEMS microstructures. A Ni layer was deposited and lift-off (Fig. 1(b)), which was used as the metal mask for the following RIE with a $SF_6/O_2$ plasma. Under the etch condition used in this work, the etch rate selectivity of SiC/Ni is more than 100 to ensure complete removal of p-SiC in the unmasked regions and etching into the n-SiC substrate, as shown in Fig. 1(c). After RIE, the Ni mask was stripped off by a Ni etchant, and another Ni layer was deposited on the backside of the sample which will be used as the anode in PEC etching.

PEC etching was employed to release the MEMS structures. Fig. 2 shows the PEC etch setup. A detailed description of the setup can be found elsewhere [11]. The 4H-SiC sample surface was immersed in a dilute KOH solution (1% in deionised water) contained in a Teflon reservoir, and was exposed to UV light from the front side by using a 100 W Hg arc lamp with a 250–400 nm bandpass filter. The output UV light from the lamp was focused on the sample surface by a 10× objective of a Fluorescence Microscope, as shown in Fig. 2(b). Pt wire was used as the cathode in the KOH solution, and Ni on the backside of the sample as the anode. When a bias is selected properly, p-SiC suspended microstructures are released by undercutting the underneath n-SiC layer, as shown in Fig. 1(d).

## 3. Results and discussion

Fig. 3 shows the SEM images of the single-crystal SiC MEMS structures developed in this study. Straight cantilevers and bridges with different lengths were attained, and close-up images show that PEC etching did not leave obvious damage to the structures. The straightness of the beams and the flatness of the membrane indicate the absence of stress gradient within the p-SiC layer. Since the geometry and layout of the suspended microstructures can be well defined by the growth of the p-SiC layer and lithography of the etch mask, this novel technique gives flexibility to fabricate different types of MEMS structures, and even nanoelectromechanical systems (NEMS) with the assistance of E-beam lithography. Since the whole MEMS system is made of single-crystal SiC, and the area and layout of

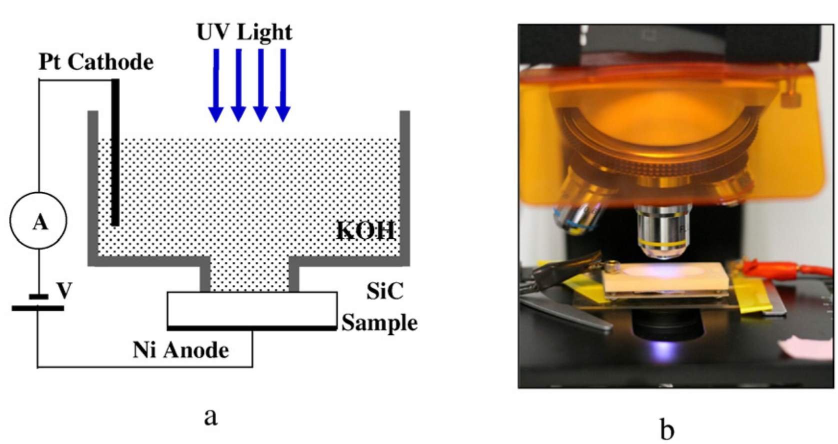


**Fig. 2.** (a) Schematic and (b) micrograph of the PEC etch setup.