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Vertical SiC taper with a small angle fabricated by slope transfer method

Yu Xin[✉], Gregory Pandraud and Paddy J. French

In this Letter, a slope transfer method to fabricate vertical waveguide couplers is proposed. This method utilises wet etched Si as a mask, and takes advantage of dry etching selectivity between Si and SiC, to successfully transfer the profile from the Si master into SiC. By adopting this method, a <2° slope is achieved. Such a taper can bring the coupling efficiency in SiC waveguides to 80% (around 1 dB loss) or better from around 10% (10 dB loss) without taper. It further increases the alignment tolerance at the same time, which ensures the successful development of a plug-and-play solution for optical sensing. This is the first reported taper made in SiC.

Introduction: Waveguides are now widely used in many areas from optical communication to bio-medical sensing. However, the alignment and coupling between optical sources/fibres and waveguides are still problematic for practical applications in some fields, especially where the plug-and-play system is needed. Traditionally used materials for optical waveguides include Si, SiO_2, SiN and SiC and waveguides made from these materials are normally sub-micron thick and several-microns wide, thus experiments need to be conducted under a microscope on a precise optical stage, making the fibre to waveguide coupling a challenge. To relieve this handling problem, couplers with wider and thicker tapers need to be added to the waveguides. Horizontal tapers can easily be obtained by pattern design and lithography, while vertical tapers with slopes need some effort. Current methods to fabricate vertical tapers include greyscale lithography [1], thermal reflow [2] and wet etch in a silicon wafer with a tilted ⟨1 1 1⟩ crystal orientation [3]. Greyscale lithography is a binary process and results in a step profile surface, while thermal reflow takes time and has edge bead effects [4, 5]. Both the step profile and the abruption of the induced edge bead will influence the optical transmission and hinder the coupling effectiveness. Furthermore, the thickness of the photoresist mask depends on the thickness of etched material and the etching ratio between them, so thick photoresist will be needed when etching hard materials. A more efficient method is here developed for fabricating vertical taper with several-micron in thickness and made of hard materials. In this Letter, we propose a slope transfer method which takes advantage of the etching rate ratio between silicon and the taper material, to transfer slope from silicon into the taper.

Design and simulations: In the waveguide design, SiC is selected as the core material due to its excellent optical, mechanical, electrical properties and also its chemical resilience. From an optical point of view, it is transparent above 0.5 µm wavelength, enabling wavelengths in the visible and the near infrared range be guided. It has a rather high refractive index generally ranging from 2.3 to 2.5 [6] or even higher, making it a promising material in optics and more preferable when fabricating bent and small radius waveguides [7]. Mechanically, SiC is robust and has a high Young's modulus making it stands out in designing freestanding structures such as thin films or bridges. Chemically, it is highly stable even in a harsh environment and it can be used in sensors for high temperature or the changeable environment. Furthermore, SiC can be deposited on wafers using various methods, such as LPCVD, PECVD and APCVD. By changing processing conditions, such as temperature and gas ratio, a-SiC or poly-SiC with adjustable refractive index and mechanical properties can be formed which offers more flexibility when designing waveguides. LPCVD shows good uniformity in fabricating thin layers, with a slow deposition rate at around 0.2 nm/min, while PECVD SiC has a lower deposition temperature (200–400°C) and a higher deposition rate making it advantageous when thicker layer and lower temperature conditions are required. Considering the excellent properties of SiC described above, it is an ideal candidate for the waveguide core material in an evanescent sensing system.

Besides the waveguide sensing structure, to achieve a plug-and-play system, couplers need to be added to the waveguide system to enhance coupling efficiency and alignment tolerance. The schematic of designed SiC waveguide with couplers is shown in Fig. 1. Simulations were done to find out how the refractive index of taper material influences coupling efficiency by changing the couplers materials (one with a higher refractive index, one with the same and another with a lower one than the coupled waveguide). Simulation schematic is shown in Fig. 2*a*. Light is excited from the fibre on the right and channelled into waveguide via taper into the waveguide. Then the transmitted light is collected at the left port. The coupling efficiency is evaluated by comparing the input and output light power. When the taper material has a higher refractive index than the waveguide, the light will not be channelled into the waveguide effectively (see Fig. 2*b*). The coupling efficiency is only half of the coupler with the same refractive index as the waveguide. When the taper material has a lower refractive index than the waveguide core, most of the light is scattered during the transmission in the taper (see Fig. 2*c*). Thus, the coupling is the most efficient (Fig. 2*d*) when the material is uniform and the taper made of the same material of the waveguide. Therefore, SiC is chosen for the coupler to be well integrated with the previously designed SiC waveguide [8]. In this Letter, a new method of fabricating vertical taper in SiC with etched silicon as a mask is presented, by which way a desired small angle slope was achieved. LPCVD and PECVD methods are combined to deposit SiC layers to guarantee that the waveguide core layer is thin and uniform while the taper layer is thick enough. Simulations on how the coupling efficiency is influenced by the taper height H and angle θ (see Fig. 2*a*) were performed in COMSOL to obtain a taper structure that can achieve optimal coupling efficiency. Results are shown in Fig. 3, indicating that the smaller angle is, the higher coupling efficiency is. For taper with the same angle, the bigger the taper height is, the larger the alignment tolerance will be.

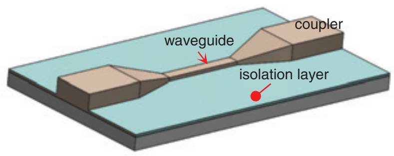

Fig. 1 *Schematic of SiC waveguide with tapers*

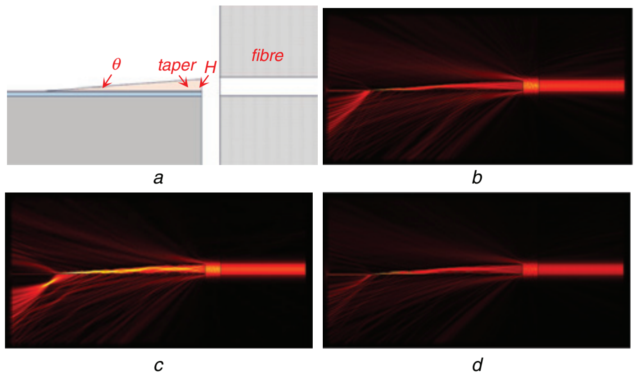

Fig. 2 *Waveguide-fibre coupling simulations*

a Waveguide-fibre coupling simulation schematic
b–d Simulation results of tapers with a different refractive index
b n_{taper} higher than $n_{waveguide}$
c n_{taper} lower than $n_{waveguide}$
d n_{taper} the same with $n_{waveguide}$

Fabrication methods: Considering that SiC is a rigid material to etch, a slope in Si is wetly etched in the first step and then the etched Si slope is used as a mask and transfer the profile into SiC in proportion to the dry etching rate ratio. The fabrication processes are designed and achieved in two flowcharts illustrated as follows:

(1) *Slope transfer with a bonding layer:* This fabrication process was described in [8]. A double side polished ⟨1 0 0⟩ wafer was firstly wet etched to get a slope of 54.74° defined by silicon crystal orientation. Then a SiC layer was deposited on the single side polished wafer followed by a photoresist layer on top, to bond with the wet-etched double side polished wafer. Then the bonded wafer was dry etched with the formed silicon profile as a mask and then the slope in Si was transferred into SiC with a certain ratio defined by the etching rate difference. A 16° slope was obtained by this flow. The SEM image of the fabricated slope is shown in Fig. 4. The bonding photoresist layer in between got burnt during the etching process and in return influenced the transferring process including etching uniformity and transferring ratio. When the slope angle is 16°, the simulated coupling efficiency is only 4% for a taper height of 6 µm. To improve the efficiency of

the coupler, the transfer process needs to be improved to achieve a surface of better uniformity and with a smaller slope angle.

(2) *Slope transfer without bonding layer:* To optimise the fabrication, the transfer photoresist layer was removed by directly depositing the masking Si layer on top of the SiC taper layer instead. The fabrication method is still taking advantage of the etching rate difference between Si and SiC for slope transfer. The process is shown in Fig. 5. Firstly, a 5 μm-thick SiC layer was deposited by PECVD under 400°C with a gas mixture of SiH_4 and CH_4 [9]. Then a thick layer of α-Si was sputtered on the SiC layer in Sigma followed by a layer of PECVD SiO_2 acting as a mask layer for wet etching. After all the layers were prepared, an etch window was open in SiO_2 and then the whole wafer was dipped into a 25 wt% TMAH solution at 85°C. A short time over etch was applied to guarantee that the Si mask was etched through to reach the SiC layer underneath. After the wet etch of α-Si in TMAH, a curved slope profile was formed in silicon. Then the wafer was etched by an SF_6/O_2 gas mixture under 10°C in Omega Trikon RIE etcher. Due to the different etching rate between Si and SiC, the profile in silicon was transferred into SiC with a different (slighter) slope under the dry etch of Omega. After finishing the whole process, the slope profile was inspected with a Keyence VK-X 3D scanning confocal laser microscope. The profile is shown in Fig. 6. Then the slope is measured on section A to be lower than 2° (shown in Fig. 7). The coupling efficiency will be greatly improved to around 70% with a taper height of 6 μm, which is efficient enough to meet the requirement of the optical sensing systems. Compared with the former process, this method skipped the bonding step, which decreased the surface roughness caused by burnt effect and non-uniformity of the bonding photoresist as cooling is difficult with the resist. The surface roughness of reactive ion etched SiC in SF_6/O_2 is measured to be lower than 1 nm [10]. The transmission loss in SiC will be way lower than 1 dB/cm according to previous research in [11]. Therefore, the total transmission loss in SiC coupler will be <1 dB. The benefit of the coupler, which decreased 9 dB insertion loss, far weighs the induced transmission loss and demonstrates such a coupler to be efficient.

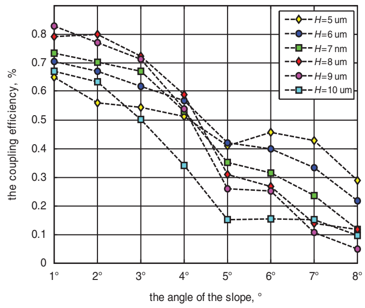

Fig. 3 *Coupling efficiency of tapers with different height and angles*

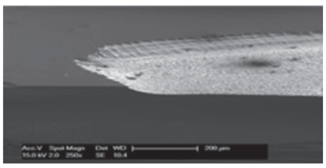

Fig. 4 *SEM image of the first fabricated slope into SiC*

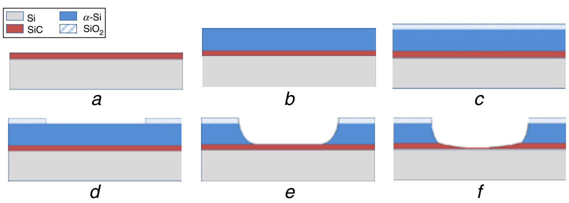

Fig. 5 *Slope transfer method flowchart*

a PECVD SiC on silicon wafer
b Sputtering α-Si on SiC layer
c PECVD SiO2 on top of Si layer
d Open etch window in SiO_2
e Wet etch into α-Si in TMAH
f Dry etching to transfer slope from α-Si to SiC

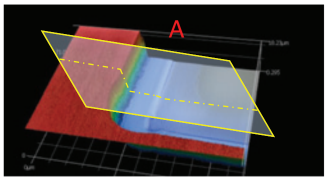

Fig. 6 *Profile of the second slope fabrication*

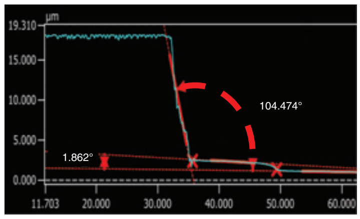

Fig. 7 *Measured angle of the second slope on plane A*

Conclusion: In this Letter, a slope transfer method was proposed to achieve a small slope in SiC which is used in waveguide taper fabrication. A <2° slope was achieved by this process. This method is demonstrated to greatly reduce the coupling loss and can be well integrated with former designed SiC waveguide, which enables the realisation of a plug-and-play system for optical sensing.

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One or more of the Figures in this Letter are available in colour online.

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