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4H-SiC Microring Resonators for Nonlinear Integrated Photonics

Yi Zheng[1], Minhao Pu[1], Ailun Yi[2], Xin Ou[2], Haiyan Ou[1]

[1] DTU Fotonik, Technical University of Denmark, Building 343, DK-2800 Lyngby, Denmark
[2] Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai, China
e-mail: haou@fotonik.dtu.dk

ABSTRACT

We demonstrate efficient four-wave mixing in high Q 4H-SiC microring resonators. We achieve a four-wave mixing conversion efficiency of -21.7 dB in a microring resonator with 79 mW pump power. Thanks to the strong light confinement in SiC waveguides with sub-micron cross-section dimensions, a high nonlinear parameter (γ) of 12.5 $W^{-1}m^{-1}$ is obtained, from which the nonlinear refractive index (n_2) of 4H-SiC is estimated to be $9.2\pm0.4\times10^{-19}$ m^2/W at telecom wavelengths.

Keywords: Nonlinear optics, integrated optics, microresonators.

1. INTRODUCTION

An abundance of nonlinear optical effects have been realized in nonlinear integrated optics, which shows great potential for a variety of applications such as high speed signal processing [1], electro-optic modulation, sensing, light amplification, etc [2]. Efficient four-wave mixing (FWM) can also lead to Kerr frequency comb generation in high quality factor (*Q*) nonlinear microresonators [3]. Therefore, tremendous effort has been made to develop nonlinear integrated material platforms and frequency combs have been achieved in different materials including silicon [4], Si_3N_4 [5], Hydex [6], Diamond [7], AlN [8], AlGaAs [9], etc.

SiC is also considered to be a suitable candidate for nonlinear integrated optics since it exhibits relatively large Kerr nonlinearity on the order of 10^{-18} m^2W^{-1}[10]. Besides, its quadratic nonlinearity is also strong (~ 30 pm/V [11]) and multi-photon absorption is absent in SiC at telecom wavelengths, e.g. ~1550 nm, due to its wide bandgap (2.4 eV-3.2 eV depending on its crystallographic type [12]). Other material properties such as CMOS compatibility, high mechanical stiffness and chemical inertness, and large thermal conductivity also make SiC an attractive platform. Moreover, point defects in SiC can be exploited for single-photon sources for quantum applications. In recent years, a few nonlinear processes have been demonstrated in SiC such as second harmonic generation [13], self-phase modulation [10] and parametric wavelength conversion [14]. In addition, Kerr nonlinearity was also reported in amorphous SiC [15]. Microresonators are key components for enhancing the efficiency of nonlinear processes due to the intra-cavity power enhancement. FWM in 3C-SiC microring resonators has been reported [16], however, the high loss of 3C-SiC microring makes it a relatively inefficient process. For nonlinear processes, high *Q* microresonators are essential since it offers large enhancement of intra-cavity optical power. In addition, as the nonlinear parameter γ expressed by $2\pi n_2/\lambda A_{eff}$ is highly dependent on the effective mode area A_{eff}, a high-*Q* microresonator with a small effective mode area is highly desired to achieve efficient nonlinear processes.

We realize efficient wavelength conversion through a FWM process in high-*Q*, 4H- SiC microring resonators with sub-micron cross-sectional dimension. –21.7 dB conversion efficiency is achieved in a 16.5-µm microring resonator with 79 mW pump power. Nonlinear parameter γ of 12.5 $W^{-1}m^{-1}$ is obtained in such high-confinement waveguides, which is over three times larger than the value achieved in 3C-SiC microresonators. Besides, we also report nonlinear refractive index of 4H-SiC at telecom wavelength range as high as ~$9.2\pm0.4\times10^{-19}$ m^2/W.

2. FABRICATION AND CHARACTERIZAION

We applied smart-cut technique to realize SiCOI wafer [17], where ~1.1 µm SiC layer was left after the smart-cut process. A wet oxidation process was applied to thin down the SiC thickness from 1.1 µm to 600 nm while the roughness was reduced from ~5.27 nm to ~0.84 nm. The device fabrication on the SiCOI wafer started with pattern definition by electron beam lithography (EBL) in hydrogen silsesquioxane (HSQ) with a multi-pass process [18],[19]. The EBL was performed using a JEOL system (JBX-9500FS) at 100-kV. The HSQ pattern was then transferred to the SiC layer using a fluorine (SF_6)-based dry etching process in an inductively coupled plasma reactive ion etching (ICP-RIE) machine. After that, an extra wet oxidation was applied to further thin down the SiC layer thickness to 500 nm and reduce the roughness for both top and sidewall surfaces. In the end, SiO_2 was deposited as the cladding material through Low-Pressure Chemical Vapor Deposition (LPCVD) followed by Plasma-Enhanced Chemical Vapor Deposition (PECVD).

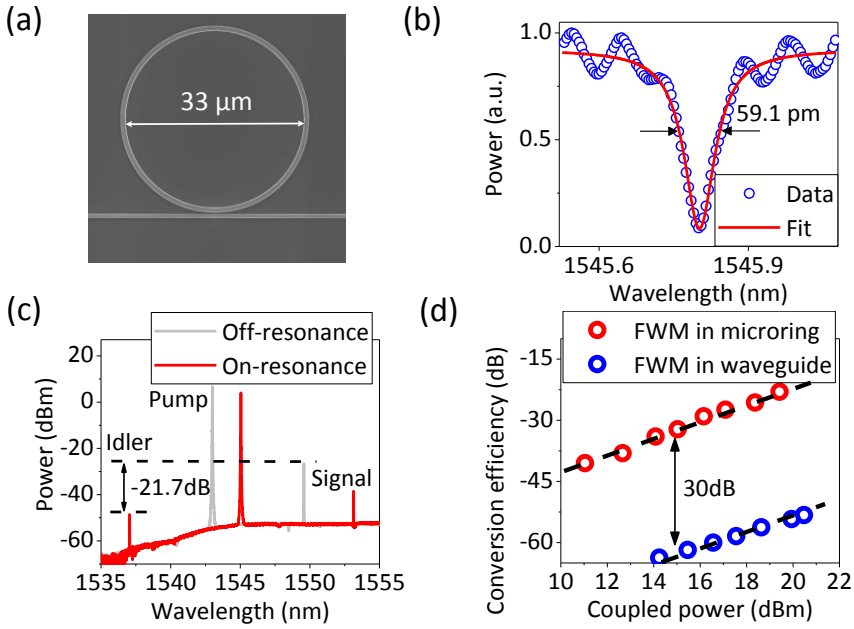

Figure 1. (a) Top-view SEM picture of a fabricated SiC microring resonator with 16.5-µm radius. (b) Measured normalized transmission spectrum of an SiCOI microresonator with fitting around 1545 nm. (c) Measured output spectra of the microresonator with the pump and signal waves off-resonance (grey curve) and on-resonance (red curve). (d) Coupled power dependent CE of a resonance in a16.5-µm radius SiC microring resonator (red) and a 3 mm long waveguide (blue).

To perform FWM experiments, we used a 16.5-µm radius microring resonator with cross-sectional dimension of 700×500 nm^2 (Fig. 1(a)), which is operated in over-coupled condition with a loaded Q of ~26,000 (the resonance linewidth is shown in Fig. 1(b)). The intrinsic Q of tested resonator was estimated to be ~70,000. In the FWM experiment, both pump and signal waves were coupled into the resonator. Figure 1(c) shows the output spectra from the resonator when the pump and signal waves are both off-resonance (grey line) and on-resonance (red line). We achieved an overall conversion efficiency (CE), defined by the ratio between the output idler power and input signal power in the bus waveguide of -21.7 dB with 79 mW of pump power. FWM conversion efficiency was also measured in a 3-mm long SiC waveguide with the same cross-sectional area as the microring resonator. As shown in Fig. 1(d), 30 dB enhancement of FWM conversion efficiency was achieved. The FWM conversion efficiency of a 104-µm-long waveguide (the physical length of tested 16.5-µm radius microring resonator) in perfect phase-matched condition (in the case of very small signal-pump detuning) can be estimated by $(P_p\gamma L_{eff})^2$, where P_p and γ are the estimated intra-cavity power and nonlinear parameter. L_{eff} is the effective interaction length of the pump and signal in the waveguide defined as $(1-e^{-\alpha L})/\alpha$, where L is the length of the device. The estimated CE was -83.5 dB. Therefore, 61.8 dB CE gain was obtained at the same pump power level in a microresonator device.

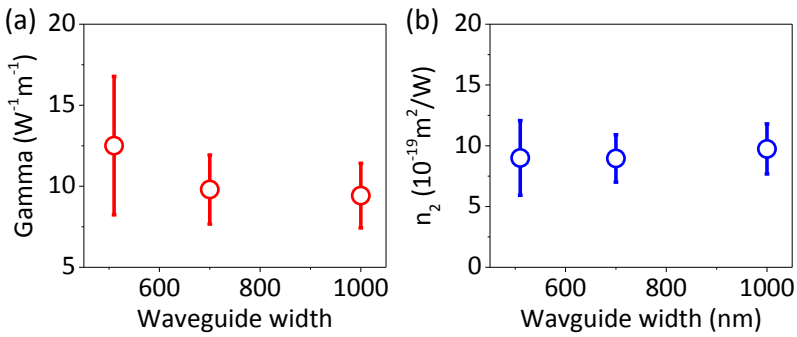

Figure 2.(a) Estimated nonlinear parameter γ and (b) nonlinear refractive index n_2 (blue) based on CE measurement on microring resonators with different cross-sectional areas.

To extract the nonlinear parameter γ, we measured the CE for 16.5-microring resonators with different waveguide widths (including 510 nm, 700 nm and 1000 nm). The red circles in Fig. 2(a) show that the estimated γ values are around 12.5, 10 and 9.4 W^{-1}m^{-1} for 500 nm thick SiC microring resonators with different waveguide widths. By calculating the effective mode areas for these waveguides, we estimated the nonlinear refractive index of 4H-SiC at telecom wavelength range is on the order of 9.2±0.4×10^{-19}m^2/W (Fig. 2(b)). The obtained γ of 12.5 W^{-1}m^{-1} is over three times larger than previous reported result in 3C-SiC waveguides [16].

3. CONCLUSIONS

In conclusion, we demonstrated efficient FWM process in 4H-SiC microring resonators. -21.7 dB conversion efficiency was achieved in a microring resonator, which is 30-dB higher than a 3-mm long waveguide at the same pump power. Highly nonlinear SiC waveguides with nonlinear parameter γ of 12.5 $W^{-1}m^{-1}$ has been realized, which is higher than previously reported value. The demonstration of this work shows potential for enabling all-optical signal processing functionalities through highly nonlinear SiC waveguides.

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