Stand-alone 3C-SiC-based Single-photon Source modules for Quantum Key Distribution

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Abstract: We propose the stand-alone 3C-SiC-based single photon source modules for Quantum Key Distribution. They emit single-mode-fiber-coupled single photons at high count rates and operate at room temperature near the telecom O-band. © 2024 The Author(s)

1. Introduction

Quantum key distribution (QKD), relying on the laws of quantum mechanics, provides an unconditionally secure data communication between remote parties. Due to practical limitations of achieving a deterministic single-photon source, it is primarily implemented using coherent light sources attenuated to the single-photon level. Nevertheless, the demand for the development of an ideal single-photon source persists, driven by security concerns related to the photon number distribution characteristics, system complexity, and challenges in long-distance transmission.
To become an ideal single-photon source for practical QKD systems, it is necessary to have the properties such as high single-photon count rate, operation in the telecom wavelength ranges at room temperature, and scalability [1]. Recently, 3C-SiC-based point defect has gained significant attention as promising quantum light sources that can overcome the drawbacks other material platforms have. However, the origin of these defects has not yet been fully elucidated [2]. For the single photons generated from emitters in semiconductor substrates, only ~1% of them actually can escape due to their high refractive index. To overcome this low collection efficiency, various structures such as solid immersion lens (SIL), microlens, micropillar, nanowire, circular Bragg grating have been proposed [3]. Despite the expected high collection efficiency, the complex fabrication processes and precise alignment required with quantum light sources make it challenging to achieve high yields.
In this paper, we demonstrate stand-alone 3C-SiC-based single-photon source modules. For this demonstration, we first improve the collection efficiency using the zirconia half-ball lens as a SIL. We then couple the collected single photons to the single mode fiber following the optical packaging process. The fabricated single-photon modules operate at room temperature with peak wavelength of 1.25 um. Under the pump power of 0.65 mW, the module emits 250 kcount/s of single photon, which is a ten-fold enhancement compared to when not using the SIL.

2. Collection efficiency improvement using solid immersion lens

We assess the improvement in collection efficiency using the SIL by calculating the variation in collection efficiency as a function of the numerical aperture (NA) of the collection optics [4]. Fig. 1(a) shows the calculated collection efficiencies for 3C-SiC (refractive index of 2.55 @ 1.3 μm), both with and without anti-reflection coating.

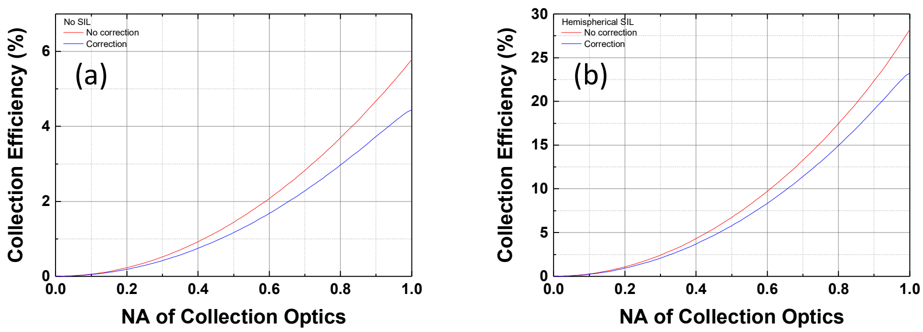

Fig. 1. Collection efficiency obtained from 3C-SiC wafers (a) without and (b) with hemispherical solid immersion lens.

We can obtain only a 2% collection efficiency with NA of 0.65. When a zirconia half-ball lens is used as the SIL, it increases to 9.8% due to the relaxed total internal reflection.

3. Fabrication

First, we searched a single-photon source in a 5 mm x 5 mm piece of 3C-SiC (111), which was grown on a silicon substrate with the thickness of 0.4 μm. We then aligned a 500 μm-diameter zirconia half-ball lens on top of it to enhance the extraction efficiency of the source. The lens was securely fixed using UV-curable epoxy as Fig. 2(a) shows. The generated single photons were coupled into single-mode fiber through two aspheric lenses. We utilized a wavelength-division-multiplexed (WDM) optical fiber (leftmost component in Fig. 2(b)) capable of separating the 976 nm pump light from the generated single photons. Finally, this submodule was packaged into a metal case. Fig. 2(b) shows the aligned the WDM fiber, 2^{nd} lens, 1^{st} lens, and 3C-SiC with SIL, from left to right.

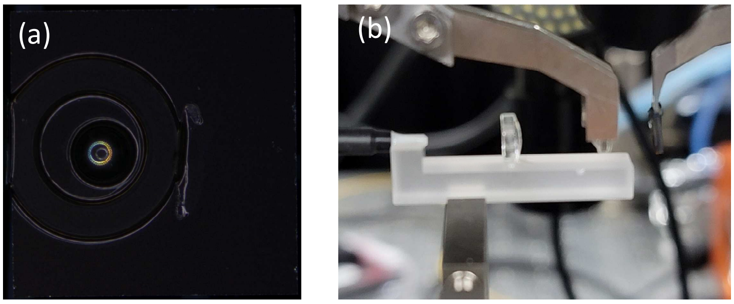

Fig. 2. A fabricated (a) 3C-SiC single-photon source with SIL and (b) alignment of WDM fiber, lenses, and source with SIL.

4. Results and Discussion

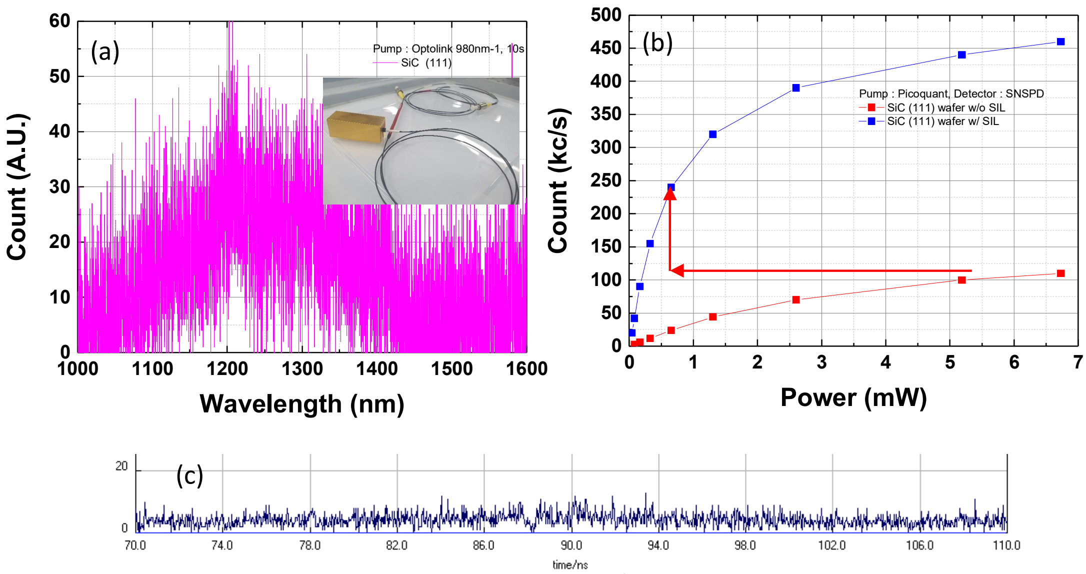

Fig. 3. (a) Measured spectrum, (b) count as a function of pump power, and (c) $g^2(0)$ of the fabricated 3C-SiC single-photon source module.

The fabricated single-photon source module is shown in inset of Fig. 1(a). This module operated at room temperature and the measured peak of the fabricated module was near 1.25 μm as Fig. 3(a) shows, which corresponds to the telecom O-band. Under the pump power of 0.65 mW, the module emitted 250 kcount/s of single photon, which was a ten-fold enhancement compared to when not using the SIL. This enhancement is due to the focused beam effect and improved collection efficiency by SIL. Improvement in collection efficiency is significantly influenced by the size of the air gap between SIL and 3C-SiC, making it crucial to pay attention to sample and SIL surface flatness and foreign particle removal during SIL alignment. The measured single-photon purity was ~0.3 as shown in Fig. 3(c).

5. Conclusions and Outlook

We have developed a stand-alone 3C-SiC-based single-photon source module operating at room temperature with the peak wavelength of telecom O-band. The single photons from a 3C-SiC chip with SIL was optically coupled to WDM fiber capable of separating the 976 nm pump beam with the generated single photons. The single-photon generation rate of this module was ten-fold enhanced at the pump power of 0.65 mW due to both the focused pump beam effect and improved collection efficiency by SIL. More improved performances are expected if the coupling optics between fiber and source are optimized.

6. Acknowledgements

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7. References

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