ULTRA-HIGH THERMAL CONVERSION EFFICIENCY IN A PROTOTYPE LIGHT SOURCE BASED ON PHONONIC MEMS STRUCTURE

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ABSTRACT

This paper presents the demonstration of a broadband light source boasting a radiation efficiency 100% higher than that of a typical infrared light-emitting diode (LED). Internal blackbody radiation efficiency can reach up to 97% based on our ideal modeling. This ultra-high efficiency is achieved through phononic MEMS technology, providing exceptional thermal isolation for a microplatform. Raman spectroscopy is utilized to estimate the thermal conversion efficiency. The microplatform is heated to 994 K with 33 μW incident blue laser power, representing that approximately 33% of absorbed radiation is retained within the platform as thermal energy in a sub-optimum condition.

KEYWORDS

Phononic Crystal, Highly Efficient Light Emitting Source.

INTRODUCTION

Recently, thermal conductivity reduction using phononic crystal (PnC) has attracted much interest due to its potential for future microelectromechanical systems (MEMS) applications [1]. Meantime, we learn that nanoscale PnC features integrated in nanowires reduce electrical conductivity to a much lesser extent compared to the reduction of thermal conductivity (k).

In this work, we make full use of this desirable property of the PnC nanowires to develop a highly efficient Si based light emitting platform, which is named "light-emitting platform (LEP)". The most common thermal emitter, the inefficient incandescent Edison light bulb, provides useful visible efficiency in the range of 5 to 10% [2]. We achieve unprecedented overall broadband infrared device efficiency in our infrared LEP "lightbulb" by resistively heating a thermally isolated micro-platform. The extreme thermal isolation of the micro-platform is achieved using support nanowires configured with a PnC patterning, providing a thermal conductivity of 1.1 W/(m·K) by our team [3]. Note that the measured thermal conductivity values demonstrate up to a 140× reduction compared to silicon's bulk thermal conductivity of 148 W/(m·K), with only a 2 to 3× reduction in electrical conductivity.

DESIGN OF THE DEVICE

A schematic of Si-LEP is shown in Fig. 1. A Si-LEP device consists of two parts: two PnC patterned Si nanowire legs and a Si-microplatform. The PnC patterned legs support the Si-microplatform with a thickness of 70 nm. This devised structure facilitates high thermal isolation, achievable through the utilization of PnC nanowire legs. The slight decrease in electrical conductivity, contrasted with the significant reduction in thermal conductivity, serves to maximize power efficiency. In other words, the device can be heated with minimal power consumption through the PnC nanowire legs, while the generated heat remains localized within the micro platform. As a result, the confined heat on the microplatform radiates infrared according to Stefan-Boltzmann's law. The internal radiation efficiency ($\boldsymbol{\eta} = {\varepsilon\sigma A T^4}/{I^2 R}$) varies according to the width of PnC nanowire legs, ranging from 80% to 97% as simulated by Finite Element Analysis.

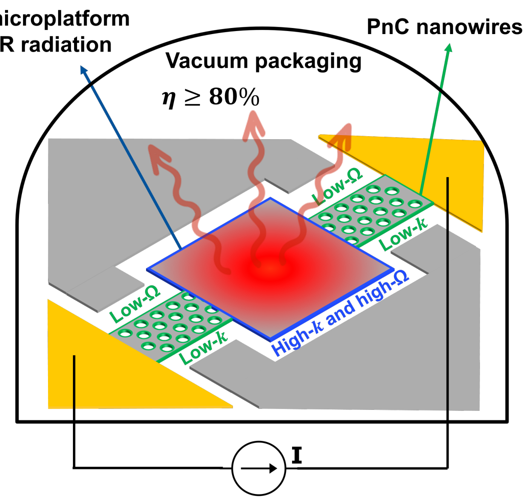

Figure 1: Schematic of designed PnC integrated Si-LEP device: Two supporting PnC nanowires and Si-microplatform in vacuum packaging.

DEVICE FABRICAION

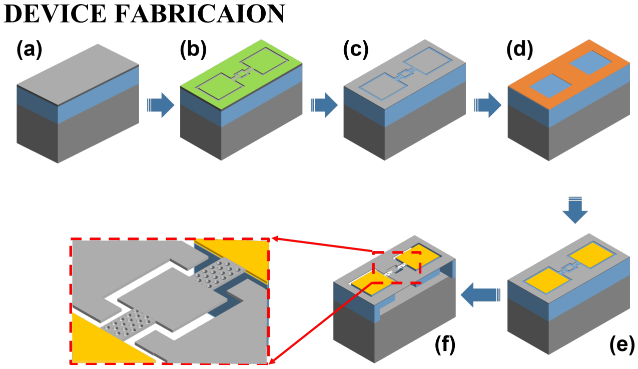

Figure 2: Fabrication process: (a) cleaned SOI substrate, (b) patterning using EBL, (c) Si top layer (70 nm) etching through DRIE technique, (d) patterning using photolithography, (e) metal (Cr and Au) deposition for contact pad, and (f) HF vapor etching to release the Si-LEP device.

Figure 2 shows the overall fabrication process. First, the device was fabricated on a single side polished silicon-on-insulator (SOI) wafer from Soitec. Polymethylmethacrylate (PMMA) (Microchem Corp.) was deposited on the wafer as a positive resist, and electron beam lithography (EBL) was used to pattern the PMMA. The patterned PMMA layer is used as an etch mask to transfer the PnC patterned nanowires and device patterns to the SOI top layer using a subsequent deep reactive ion etching (DRIE) process. Last, dry mode hydrofluoric (HF) etching was performed to etch the buried oxide layer under the PnC supported Si-microplatform, releasing the device from the substrate.

EXPERIMENTAL RESULTS

Figure 3 displays the fabricated Si-LEP along with an expanded view of the nanowire revealing its PnC structure. A Si-LEP device consists of two parts: two 0.5 µm width PnC patterned Si nanowire legs and a Si-microplatform (10 × 10 µm^2). The patterned PnC features a neck size ranging from 20 to 30 nm and a nanohole diameter ranging from 80 to 100 nm. As depicted in the magnified SEM images, the hole arrays are structured in hexagonal lattices, strategically designed to optimize phonon scattering, thereby minimizing thermal conductivity [4].

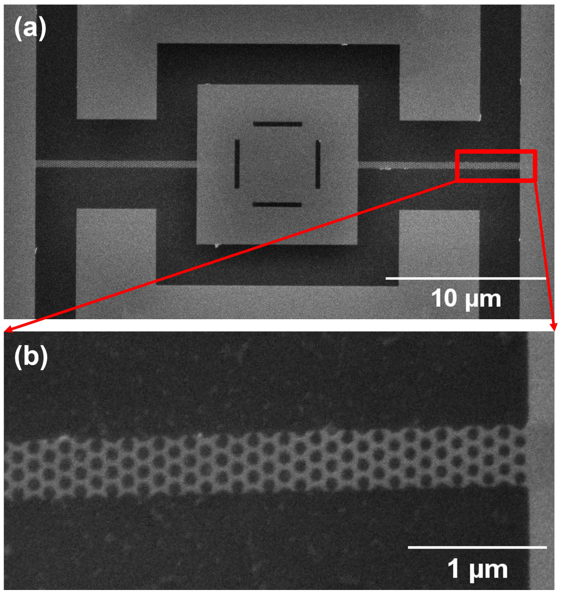

Figure 3: (a) Topside view of an LEP pixel and (b) an expanded view of the nanowire showing its PnC structure.

The fabricated device has been characterized using a novel test structure employing Raman sensing within a vacuum system, and the thermal conversion efficiency has been determined [5]. The fundamental Stefan-Boltzmann law, expressed as $W = \varepsilon\sigma T^4$, provides the net power density of blackbody radiation emitted by an object based on its thermal temperature. The temperature is expressed in degrees Kelvin. All surfaces emit heat according to Plank's Law.

In this experiment, a blue (405 nm) laser power of 33 µW was used to heat the platform, and a green laser (532 nm) with 6.85 µW laser power was employed to acquire the Raman signal. Figure 4 (a-b) presents the experimental results, while the following equation shows the method employed in this work for calculating thermal conversion efficiency:

$$\boldsymbol{\eta} = \frac{\boldsymbol{\sigma A T^4}}{\boldsymbol{P_{incident}\alpha}} \qquad (1)$$

where η, σ, A, T, $P_{incident}$ and α represent the thermal conversion efficiency, Stefan-Boltzman constant, microplatform area (10 × 10 µm^2), temperature, incident laser power and absorption coefficient of silicon at a wavelength of 405 nm, respectively. As shown in Fig. 4(a), the shifted Raman peak position is 501.39 cm^{-1}, which has moved by 18.21 cm^{-1} compared to the Raman peak at room temperature. The Raman peak shift is utilized to infer temperature based on the Balkanski theory equation [6]. The measured temperature of the heated Si-LEP was 994 K. Utilizing this temperature and equation (1), it was determined that approximately 33% of the absorbed radiation is retained within the platform as thermal energy.

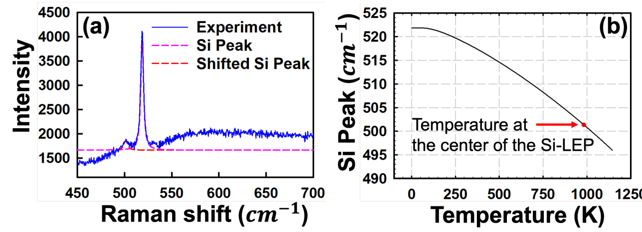

Figure 4: Raman thermography results of suspended Si-LEP. (a) Raman peak shift with an incident laser power and (b) Temperature dependence of the Raman peak position.

CONCLUSION

We present a novel broadband infrared light-emitting source, denoted as LEP based on silicon, which demonstrates significantly improved efficiency using PnC patterned nanowire structures. By incorporating these PnCs and utilizing a thickness of 70 nm, we were able to achieve a dramatic reduction in thermal conductivity (***k***). This resulted in exceptional thermal isolation without significantly affecting the electrical conductivity. Remarkably, the device achieved a temperature of 994 K solely through incident laser power of 33 µW, indicating a conversion of 33% of the incident laser power into a heat source. Please note that this demonstration does not include the results of experiments regarding internal radiation efficiency ($\boldsymbol{\eta} = {\varepsilon\sigma A T^4}/{I^2 R}$). Further experimental test is required to confirm a 97% internal radiation efficiency more precisely.

ACKNOWLEDGEMENT

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