Extended Abstracts of the 2018 International Conference on Solid State Devices and Materials, Tokyo, 2018, pp533-534

Hybrid carbon nanotubes integration in silicon photonic platform

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Abstract

We report on the integration of carbon nanotubes in silicon micro-cavities to develop optically and electrically light sources at wavelengths from 1300nm to 1600nm. Strong light coupling from carbon nanotubes was demonstrated into silicon photonics resonators, nanobeam cavities and slot photonic crystals cavities.

I. Introduction

On-chip integration of all photonic components in the silicon platform is an important goal to accomplish high efficiency, low energy consumption, low cost and device miniaturization. However, silicon photonics platform does not have efficient light emitter in the telecommunication wavelength range (from 1.3µm to 1.55µm). Hence, hybrid integration of III-V materials is commonly adopted for the implementation of lasers on silicon chip. Nevertheless, these heterogeneous integration schemes compromise the low cost of using silicon [1].

Carbon nanotubes (CNTs) have recently been proposed as an attractive one-dimensional light emitting material [2]. Interestingly, semiconducting single wall carbon nanotubes (SWNTs) are a versatile material with room temperature light detection and emission in the near-infrared wavelength range. SWNTs also exhibit intrinsic room temperature optical gain [3], which makes them a very promising candidate for the development of lasers in Si photonics. In addition, SWNTs have shown compatibility with Si CMOS process from theirs studies in microelectronics. Furthermore, recent advances in polymer-assisted selection of semiconducting SWNT and deposition techniques, poise this solution-processed approach to deliver a high quality material produced at large volumes and low cost. As SWNTs exhibit wide spectrum emission, characteristics of their chirality, resonant emission enhancement in Si microcavities with high quality factors was used to provide tunable spectral selectivity. Here we present the experimental demonstration of coupling SWNT photoluminescence into slot photonic crystal micro-cavities, strip micro-ring resonators and nanobeam cavities implemented in standard silicon-on-insulator wafers. We engineered the resonant modes of those structures in the datacom O-band (around 1300 nm wavelength), achieving up to 180 fold narrowing of SWNT emission in slot photonic crystal cavities and comb-like spectral response covering a 100 nm bandwidth in Si micro-ring resonators.

II. Integration Of SWNT In Slot Photonic Crystal Micro-Cavities

Silicon slot photonics crystal micro-cavities leverage the high index contrast and the photonic bandgap effect to tightly confine resonant modes within the low index slot region, resulting in evanescent fields orders of magnitude larger than conventional waveguides of the same cross-section [4]. By modulating the longitudinal lattice parameter, it is possible to form microcavities with comparatively large quality factors, with reduced mode volumes.

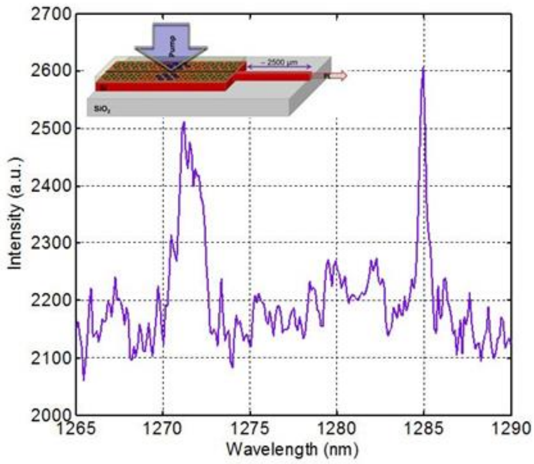

Fig.1. Photoluminescence signal collected from Si bus waveguide for Si slot photonic crystal micro-cavity.

We have optimized the micro-cavity to yield a fundamental resonant mode around 1285 nm wavelength (within the emission range of our SWNTs), with estimated ratio between quality factor and mode volume (Q/V) exceeding 300000. We prepared a high-purity SWNT solution and deposited it onto the micro-cavities by drop-casting. To characterize the ability of Si microcavity to enhance and couple SWNT photoluminescence to the output waveguide, we illuminated the deposited SWNT from the top with a Ti:Sapphire laser. We collected the generated signal, coupled to Si bus waveguide, with a lensed fiber at the chip facet. Figure 1 shows the collected photoluminescence spectrum when the excitation wavelength is set to 740 nm. The photoluminescence spectrum presents two sharp peaks, around 1285 nm and 1271 nm wavelengths, which are a clear signature of SWNTs photoluminescence coupling to the fundamental and second order modes of the photonic crystal cavity. These photoluminescence peaks have quality factors of Q~3600 and Q~700, in very good agreement with calculated results and the linear characterizations.

III. Integration Of SWNT With Silicon Micro-Ring Resonators

Micro-ring resonators are widely used in silicon photonics as they allow flexible design of multiple resonant modes covering wide spectral ranges. The spectral spacing of the resonant modes can be easily adjusted by varying the ring diameter and the waveguide geometry, thus giving the possibility to precisely tune the resonances at specific wavelength range.

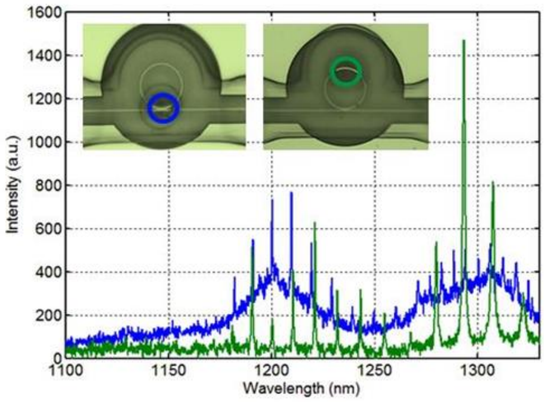

Fig.2. PL intensity as a function of the wavelength for two different scenarios. Blue line: interaction region is in the ring-to-bus coupler. Green line: interaction within the ring.

We already demonstrated integration of SWNT emission in Si micro-ring resonators [5]. However resonant enhancement was seriously limited by undesired absorption from non-excited SWNTs. Indeed, a part of the photoluminescence signal generated by excited SWNTs was absorbed by non-excited SWNTs which are onto optical propagation pathways. To overcome this limitation we have developed a selective deposition process. We cover the silicon structures with a thick HSQ (Hydrogen Silses Quioxane) layer, open windows in the regions of interest and drop-cast our SWNT solution. We can then engineer the interaction region into the photonic structures, obviating unwanted absorption effects. At the same time we still allow simple drop-casting deposition process. As an illustrative example, Fig. 2 shows the collected PL spectrum for two Si micro-resonators, one with the interaction window in the ring-to-bus coupling region (blue line and SEM on the left), and another with the interaction region within the ring (green line and SEM on the right). The micro-ring with the interaction window in the ring-to-bus coupling region exhibits two wideband lobes, around 1.2µm and 1.3µm wavelength, that correspond with the emission of our polymer-sorted SWNTs solution. We observed a set of remarkably sharp resonance enhancement peaks produced in the Si micro-ring. Interestingly, when we placed the interaction window within the ring, it is possible to remove the SWNT background emission, substantially improving the signal-to-noise ratio.

These results pave the way for the realization of integrated sources with high spectral purity operating within the O-band, based on the combination of SWNTs and Si micro-resonators.

IV. Conclusions

In summary, we reported on the integration of SWNT emission into different Si micro-resonators, including slot photonic crystal micro-cavities and strip micro-ring resonators. We also presented a selective integration approach that uses a patterned HSQ over-layer to provide flexible control over the waveguide-to-SWNT interaction while allowing simple drop-casting deposition process. These results open new perspectives for the integration of SWNT onto silicon photonic devices with the potential for the realization of cost-effective on-chip sources operating at room temperature in the near-infrared.

Acknowledements- This project has received funding from the European Union through the FP7 FET Project CARTOON (Contract FP7-618025).

References

[1] Vivien, L. and Pavesi, L., Handbook of silicon photonics, Taylor & Francis, 2013.

[2] Saito, R., Dresselhaus, G. and Dresselhaus, M. S., Physical Properties of Carbon Nanotubes, Imperial College Press, 1998.

[3] Gaufrès, E., Izard, N., Le Roux, X., Marris-Morini, D., Kazaoui, S., Cassan, E. and Vivien, L., Optical gain in carbon nanotubes, Appl. Phys. Lett. Vol. 96, no. 23, pp. 231105-231108, 2010.

[4] A. Di Falco, et al., “Dispersion control and slow light in slotted photonic crystal waveguides,” Appl. Phys. Lett., vol. 92, 083501-1-083501-3, 2008.

[5] A. Noury, et al., “Enhanced light emission from carbon nanotubes integrated in silicon micro-resonator,” Nanotechnology, vol. 26, no. 34, pp. 345201-8, 2015.