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Review

A review of recent progress in lasers on silicon

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ABSTRACT

The absence of integrated sources of light has always been regarded as a serious obstacle to silicon photonics. The inherent indirect band structure makes silicon a poor emitting material, while epitaxial lasers on Si instead face challenges from the large power loss at the interface. Overcoming these problems is the one indispensable step before the realization of efficient photonic chips, and this perspective gives huge impetus to the development on light sources on silicon. This paper provides a review of recent progress made in 2011 on lasers on silicon.

Contents

1. Introduction

Complex optoelectronic integrated circuits with low cost and high functionality are one ultimate goal for silicon photonics [1–4]. Early development in this area can be traced back to the pioneering work by Soref and Bennett more than 20 years ago [5]. During the last two decades, Si photonics has increasingly been regarded as one of the most promising solutions to the chip-to-chip communication bottleneck of CMOS based integrated circuits. As a result of the increasing interest from researchers in this area, we have witnessed a huge technology boom in the last few years, with some important breakthroughs, such as the demonstration of ultrafast Si modulators [6], the fabrication of germanium-on-silicon detectors with high-quality bonding [7], and the development of commercial Si-based CMOS photonics chips [8]. Moreover, some new ideas and materials are also beginning to offer additional possibilities in the field, for example, researchers are now considering th'e incorporation of graphene into Si photonics [9], and currently graphene-based modulators and photodetectors have both been reported [10–12].

In spite of this exciting progress, the most challenging requirement for Si photonics is the development of an effective on-chip light source. Silicon has an indirect bandgap, so the recombination of electron–hole pairs is a phonon-mediated process and this leads to a low emitting efficiency [13,14]. Early research focused on the use of quantum confinement to squeeze light from pure Si. Although electroluminescence has been observed by several groups [14–16], the output power of quantum dot lasers is unsatisfactory, together with some reliability and reproducibility problems [1]. Current research mainly focuses on the alternative mechanisms including: stimulated Raman scattering (SRS) [17,18], rare-earth doping [14,19], the use of epitaxial III–V materials [20] and hybrid laser technologies [21,22]. Table 1 is an attempted summary of the basic information of each kind of

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lasers, which includes emitting wavelength, modulation speed, standard size and their own advantages over each other [23–46]. Since there are many choices of the physical structure of lasers, only some typical examples are chosen when describing the size of lasers.

It can be observed that each kind of lasers has their own property and advantages when applying in silicon photonics. The progress of these kinds of lasers before last year had been summarized comprehensively in [1–4,12]. Instead of reviewing the history, this paper provides an evaluation of the progress made on the lasers in Si photonics over the last year.

2. Stimulated Raman scattering

The idea of applying SRS in silicon waveguides to realize silicon amplifiers and lasers was first proposed in 2002 [47]. When incident light is absorbed by spontaneous scattering, an electric polarization is induced, and then two different radiations with lower and higher frequencies than incident light are produced, these are known as anti-Stokes and Stokes transitions, respectively. If a pump and signal beam are present simultaneously with frequency resonant at the Stokes transitions, the signal beam triggers the generation of another Raman Stokes photon and SRS is realized and amplification becomes possible [2,17]. The application of SRS in Si waveguides began to attract strong interests since 2002 [18,48] and two years later, the first Si Raman laser was proposed [16,49]. However, achieving a net gain in a Si waveguide proved to be difficult due to optical losses caused by large free carrier absorption (FCA) [50–52]. This encouraged continued efforts to reduce the free-carrier lifetime and to minimize FCA. One solution was to use a reverse biased p–i–n diode Si waveguide to sweep free carriers away and thereby reduce the corresponding carrier lifetimes to around 1 ns [51]. Based on this idea, the first CW Si Raman laser was realized with pump power of around 182 mW at a bias voltage of 25 V [51].

Recently, an approximately fivefold enhancement of gain coefficient has been demonstrated using Si nanoparticles embedded in a continuous silica matrix (Fig. 1(a)). Using a 1427 nm continuous-wave (CW) pump laser, the experiment mounts a sample parallel to the path of laser and prepares for TEM observation (Fig. 1(b)). A dichroic filter and a long pass filter are used to separate the probe from pump. Amplification of Stokes signal is measured to be up to 1.4 dB/cm at 1542 nm (Fig. 1(c)). Larger gain as well as smaller threshold than the values in bulk Si systems were observed (Fig. 1(d)) [53].

High pump power is usually required in Raman lasers [54], which will induce another optical loss mechanism called two-photon absorption (TPA).TPA is a process where two photons are simultaneous absorbed by an electron that excited to a higher energy state and thereby increase the lifetime of the electrons. To reduce the loss from TPA, recent trials have focused on slowing down the pump or the Stokes signals for low-pumped power [55,56]. Alternate strategies have included experimentation with

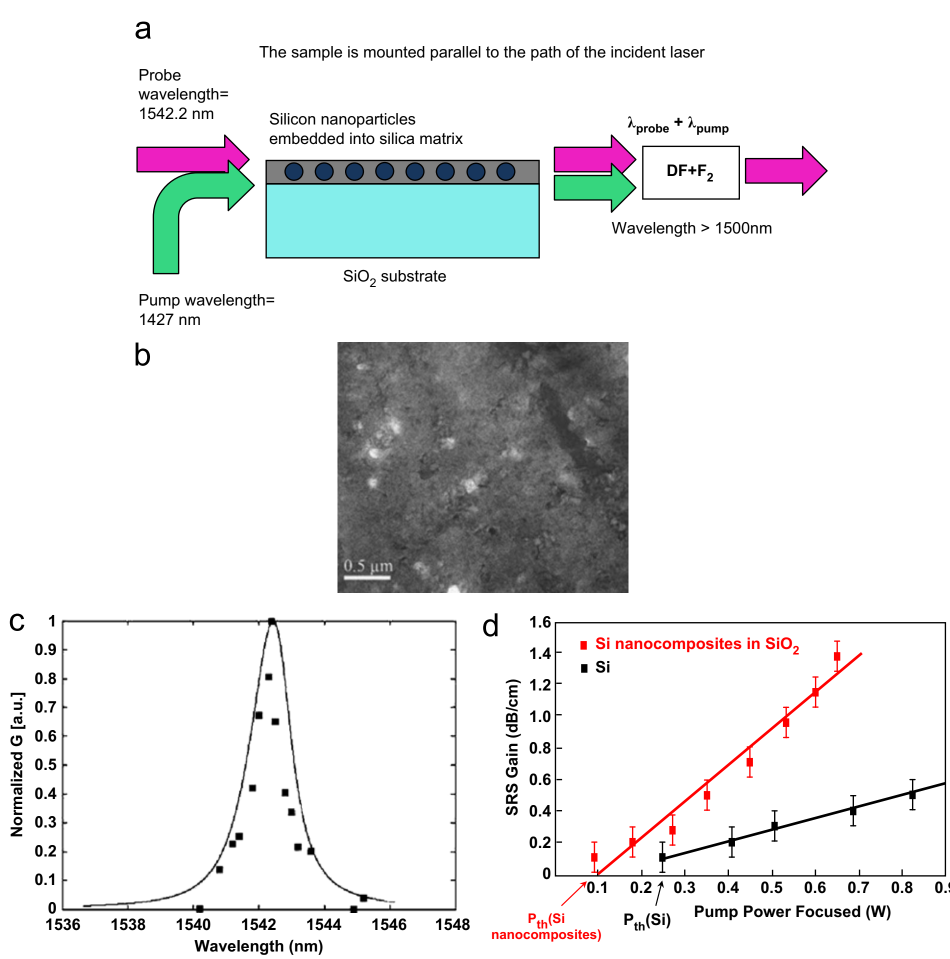

Fig. 1. (a) Scheme of the CW pump-Raman laser, DF: dichroic filter, F_2: long-pass filter at 1500 nm. (b) Si nanoparticles are shown as white spots by STEM micrograph. (c) The measured fractional change in the probe beam (G) as a function of the probe laser wavelength (solid line: theoretical value, Separated square: practical results). (d) The comparison of SRS gain (dB/cm) in Si nanocomposites (red) and bulk Si (black). Figures are taken from [53]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)