Novel Semiconductor Waveguides for Nonlinear Photonics

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***Abstract*—Nonlinear semiconductor photonics is a buoyant research field. Although most work has made use of conventional silicon waveguides on-chip, there are advantages in moving to new geometries, or materials, to improve device integration and functionality. Here I review progress in the development of novel semiconductor waveguides, both fibre and chip-based, for nonlinear applications.**

***Index Terms*—Nonlinear optics; Semiconductor photonics; Fibre optics; Waveguide fabrication**

I. INTRODUCTION

Over the past two decades nonlinear semiconductor photonics has generated significant attention within applications spanning optical communications to environmental sensing and healthcare. The majority of this work has made use of the well-established silicon-on-insulator (SOI) platforms, by leveraging the extensive microelectronic fabrication capabilities that allow for the production of waveguides with high confinement and low losses [1]. However, there are advantages in moving to new geometries, or new materials, to extend the transmission coverage or improve the device integration. In this tutorial I will review a range of different semiconductor waveguide platforms that have been exploited for nonlinear applications, including putting ‘old’ semiconductor materials into fibres and investigating ‘new’ materials on-chip. Nonlinear demonstrators will be presented for various waveguide structures that support applications across a broad wavelength regime spanning the telecom bands up to the mid-infrared.

II. WAVEGUIDE DESIGN AND FABRICATION

Two different different classes of semiconductor waveguide will be considered. The first is the emerging semiconductor core fibre platform, as illustrated in Fig. 1(a-c). These fibres have some similarity with the more traditional planar structures in that typically the high-index semiconductor material is embedded in a low index glass cladding, resulting in tight mode confinement and high nonlinearity. However, unlike the planar platforms, the fibres can be produced using high-volume fibre drawing methods that result in the rapid production of long fibre lengths, with pristine core/cladding interfaces, at low costs [2]. Moreover, the fibres are compatible with conventional fibre post-processing procedures, such as tapering

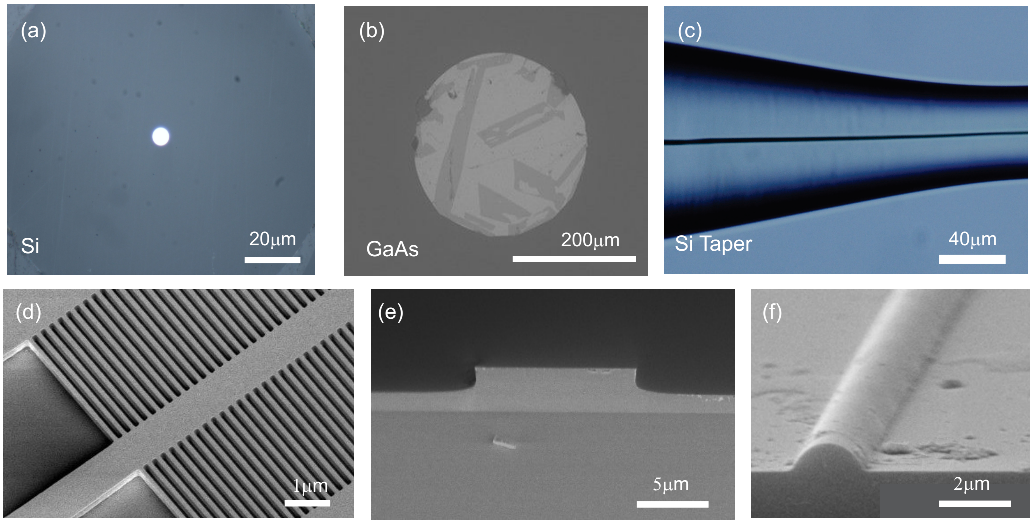

Fig. 1. (a) Silicon core fibre. (b) GaAs core fibre. (c) Tapered silicon core fibre for optimised coupling and dispersion engineering. (d) Suspended silicon-on-insulator waveguide. (e) Germanium-on-silicon waveguide. (f) Polysilicon waveguide formed via deposition and laser recrystallization.

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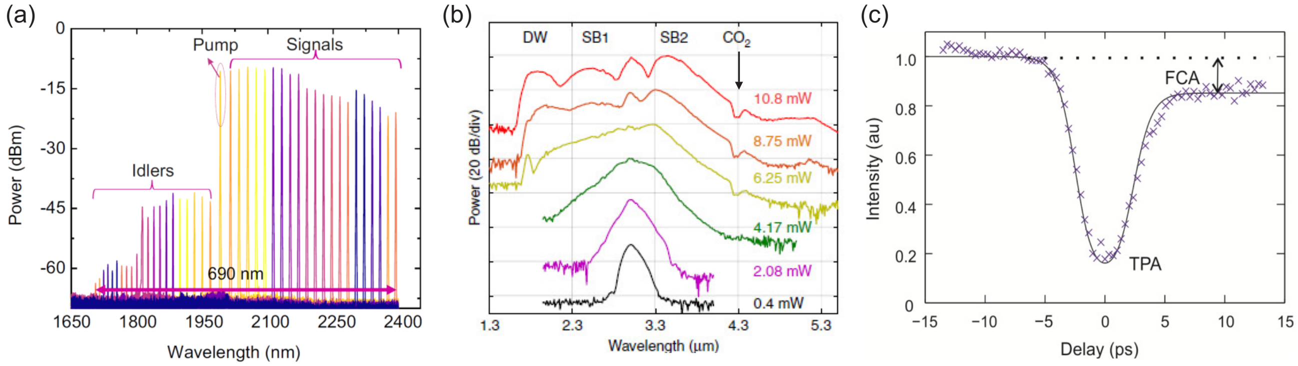

Fig. 2. (a) Four-wave mixing in a silicon fibre pumped at $\sim 2\,\mu$m. (b) Supercontinuum generation in a silicon fibre pumped at $\sim 3\,\mu$m. (c) Two-photon absorption modulation in a germanium-on-silicon waveguide pumped at $\sim 2\,\mu$m.

and splicing, which allows for further optimization of the waveguide properties [3] as well as a route for seamless integration with other fibre infrastructures [4]. Using the drawing method, a range of fibres have been produced with different semiconductor core materials, including germanium [2], silicon-germanium [5], and gallium arsenide (GaAs) [6]. As well as offering access to different transmission windows, materials such as GaAs also provide access to second order nonlinear processes that are typically absent from fibre platforms.

The second class of waveguides that will be discussed take on a more traditional planar format used for integrated photonic circuits and systems, as displayed in Fig. 1(d-f). However, similar to the fibre work, the focus will be on materials and structures that can operate in new transmission windows or can improve the interconnection between different components, including planar to fibre coupling. Examples of some of the more exotic structures include SOI waveguides that have been suspended to extend the operation beyond the low loss window of the silica cladding [7], germanium-on-silicon waveguides that can operate even further into the mid-infrared [8], as well as deposited materials such as polysilicon [9] and silicon-germanium [10] that can be trimmed, tuned or shaped. Significantly, the deposited materials are also compatible with a wider range of cladding materials, and allow for the development of multilayer structures and 3D tapered couplers for improved fibre connection [11].

To support nonlinear propagation, it is critically important that the semiconductor waveguides can be designed and fabricated to have low losses with accurate control of the dispersion properties. The latter point is required to facilitate access to the different nonlinear processes, some of which, such as four-wave mixing (FWM), require strict phase matching of the newly generated frequency components [1], [12]. The dispersion properties are usually engineered through careful design of the waveguide structure, including the choice of cladding material and the core dimensions. Thus, the transmission properties of the different waveguide classes will be compared in detail, allowing for a comprehensive discussion on their suitability for various applications, operating wavelengths and handling powers.

III. NONLINEAR DEMONSTRATIONS

For semiconductor waveguides fabricated from group IV semiconductors such as silicon and germanium, the dominant nonlinearities are associated with the third order susceptibility $\chi^{(3)}$. Although most nonlinear demonstrations in these structures have taken place in the telecom band, thanks to the ready availability of sources and diagnostics in this region, more recently attentions have been turning to wavelengths $\geq 2\,\mu$m [1], [13]. This is in part because of the desirable nonlinear properties of the materials in this region, but also because the linear losses can be lower in the engineered waveguide designs [14]. Fig. 2 illustrates several $\chi^{(3)}$ nonlinear processes in waveguides that have been optimized for operation at wavelengths beyond $2\,\mu$m. Fig. 2(a) shows the broad spectral coverage achievable via FWM using a tapered silicon core fibre with a precisely engineered dispersion profile and a low linear loss of $\sim 0.5\,$dB/cm [15]. Significantly, the wavelength conversion spans from the telecom band up to the mid-infrared, providing a convenient means to translate signals between these two important spectral bands.

Fig. 2(b) then shows a high-brightness supercontinuum spectrum spanning almost two octaves, obtained when pumping an asymmetrically tapered silicon core fibre at $\sim 3\,\mu$m, with a loss of $< 1\,$dB/cm [16]. Specifically, the tapered fibre was designed with a short output coupling section to minimise the interaction of the long wavelength light with the lossy silica cladding, which enabled the red edge of the spectrum to be extended well beyond the previous results obtained in SOI waveguides by around $2\,\mu$m. More recently, by integrating a silicon core fibre within a traditional silica fibre network, it has been possible to use the highly nonlinear semiconductor element to generate a high-power, broadband comb source with spectral features desirable for use in multichannel telecommunications systems, highlighting some of the benefits of the fibre geometry [17].

The final demonstration in Fig. 2(c) makes use of the imaginary component of $\chi^{(3)}$ to show all-optical modulation in a germanium-on-silicon waveguide with losses $\sim 3\,$dB/cm [18]. Here the modulation of a weak probe is induced via a two-photon absorption (TPA) process, using a high power pump at $1.95\,\mu$m. The measured absorption profile shows an ultra-fast response on the timescale of the $5\,$ps pump pulse, with an extinction ratio of $8.1\,$dB. Importantly, this is the highest reported extinction obtained in any of the group IV waveguides to date, which is attributed to the very large nonlinear absorption of the germanium core. Moreover, as the TPA parameter for germanium remains strong across the $2-3\,\mu$m range, it should be straightforward to extend this scheme to develop high-speed, high-extinction modulators across the entire region. Thus this work serves to further highlight some of the benefits in expanding the nonlinear optical research endeavours beyond the conventional SOI platforms.

IV. CONCLUSION

The nonlinear performance of various semiconductor core waveguides has been discussed, including structures fabricated in both fibre and planar forms. Specific focus has been placed on novel designs that make use of new waveguide geometries or new materials to extend the operation and functionality of semiconductor photonic systems. By continuing to explore the full range of possibilities for semiconductor waveguides, it is likely that new avenues for exploration and application will emerge.

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