PLASMONICS

Electrifying plasmonics on silicon

The realization of electrical sources of surface plasmon polaritons using complementary metal oxide semiconductor technology is a significant step towards silicon-compatible nanoscale photonic devices.

Aaron Hryciw, Young Chul Jun and Mark L. Brongersma

Rapid advances in nanophotonics are giving rise to remarkable data-processing and light-transport capabilities that have the potential to enhance computer performance dramatically. The realization of this objective requires seamless integration of newly emerging nanophotonic devices with more conventional nanoelectronics components. Silicon could provide an ideal platform for the marriage of these distinct technologies. However, the integration of plasmonic components with silicon has been hampered by the lack of an intrinsic source of surface plasmon polaritons (SPPs) compatible with silicon-based complementary metal oxide semiconductor (CMOS) fabrication techniques. In *Nature Materials*, Robert Walters and colleagues take a significant step towards this goal by presenting an electrical source of SPPs using light emitters that are compatible with silicon-based fabrication techniques (Fig. 1)[1].

The silicon microelectronics industry has witnessed a continual progression towards more compact, high-speed and power-efficient devices over many decades. At present, CMOS foundries are capable of generating truly nanoscale devices composed of complex and intertwined dielectric, semiconductor and metallic structures. Together with the impressive advances in electronic and photonic-device simulations, an increasingly wide variety of integrated optoelectronic functionalities can be realized using mature silicon technology.

The field of plasmonics is taking an increasingly prominent role in the design of future silicon-based optoelectronic chips. This relatively new device technology is based on the manipulation of SPPs — electromagnetic waves that propagate along a metal surface and show a strong coupling to free electrons in the metal. Initially, plasmonics was primarily focused on passive routing of light in waveguides with diameters much smaller than the wavelength of the light. However, as the propagation length in such high-confinement SPP waveguides is limited to a few tens of micrometres, they have not necessarily been perceived as a superior alternative to high-index dielectric waveguides. It is however important to realize that the size of dielectric waveguides is ultimately limited by the fundamental laws of diffraction, which is much larger than the electronic devices on a chip. Plasmonic devices and their subwavelength dimensions are uniquely capable of reconciling this mismatch in size, bridging dielectric microphotonics and nanoelectronics[2].

In addition to passive waveguides and light-concentrating structures, active plasmonic devices have in recent years opened exciting new pathways to switch and detect light in ultracompact geometries that meet or even exceed the stringent requirements of CMOS technology[3,4]. Walters and co-workers show how recent breakthroughs in plasmonics may now add a crucial ingredient: CMOS-compatible plasmonic sources. Such SPP emitters could play a critical part in chip-scale optical-information links or allow new integrated biosensing applications. An electrically pumped SPP emitter was previously demonstrated by Koller *et al.*[5]. In their device, aluminium and gold electrodes were used to inject charge into a light-emitting organic layer; conveniently, these metal contacts also make up the waveguide that carries the SPPs emitted by the organic compound. Walters and co-workers have now created a silicon-based source for which the operation principle is similar to Koller's device, but that crucially now uses Si nanocrystals as the active medium. Furthermore, the device fabrication used by Walters and colleagues capitalizes on recent advances in atomic layer deposition and low-pressure chemical vapour deposition processes that proceed at sufficiently low temperatures (~300 °C) to be compatible with back-end CMOS processing.

This type of design featuring two closely spaced metal films offers exciting added advantages that are vital for realizing power-efficient optical sources (Fig. 2). It was recently shown that the highly confined modes of such metal–dielectric–metal (MDM, also known as metal–insulator–metal, MIM) plasmonic waveguides profoundly alter the light-emission properties of optical emitters located between the metals[6]. In particular, the radiative decay rate of excited emitters can be increased by more than an order of magnitude, because SPP emission provides an efficient electromagnetic decay pathway. This is a direct consequence of the Purcell effect, which states that the radiative decay rate is not an intrinsic property of an emitter, but can instead be affected by the local environment. The large modification of the decay rate in these plasmonic structures is primarily attributed to the small size of the SPP mode, which directly translates to a strong coupling to the SPP emitter. Similar beneficial effects have

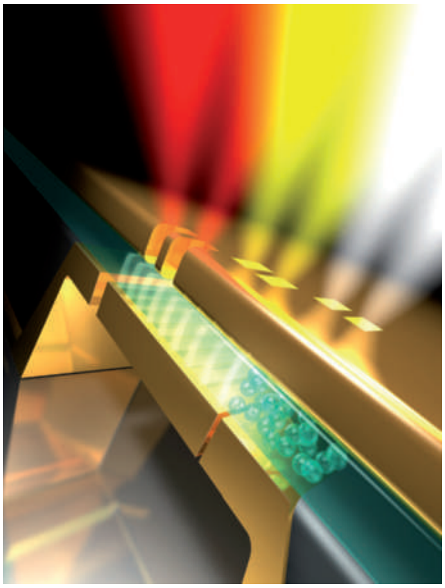

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Figure 1 | An artist's rendition of an SPP source. Silicon nanocrystals (shown in green) synthesized by a low-temperature, CMOS-compatible synthesis technique emit SPPs into an MDM plasmonic waveguide on electrical excitation. Nanoscale holes in the top metal contact can be used to couple propagating SPPs of a desired wavelength to free-space photons.

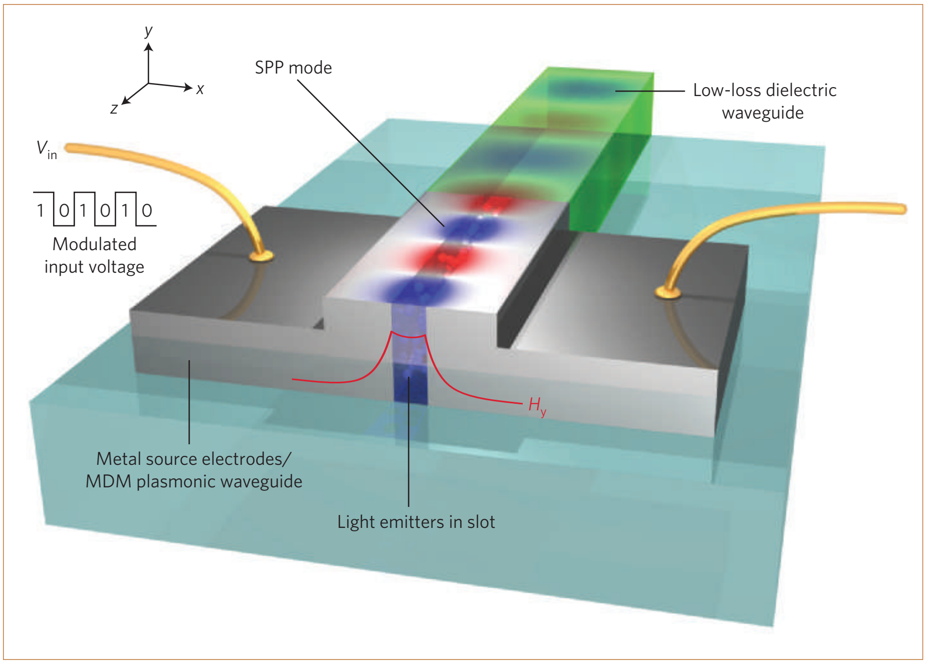

Figure 2 | Schematic of an incoherent plasmonic slot source coupled to a low-loss dielectric waveguide. The metallic regions serve as electrical contacts that sandwich a light-emitting medium, while simultaneously defining a high-confinement MDM plasmonic waveguide. On electrical injection (V_{in}), SPPs are produced in the slot; this highly confined mode is shown schematically in terms of the dominant magnetic field (H_y) profile. By modulating V_{in}, the output light can be modulated to encode information. The compactness of the source region ensures that a high fraction of the SPP mode is converted to photons in a low-loss dielectric waveguide. The dielectric waveguide then carries the information to its destination.

been predicted for other high-confinement metal oxide semiconductor and silicon-slot waveguides, opening the door to the development of an entire new set of silicon-based sources[7–9].

In stark contrast to the narrowband Purcell enhancements attained in high-quality-factor optical resonators, the observed enhancements in high-confinement waveguides are very broadband in nature. This enables effective use of emitters across the entire visible and near-infrared spectrum to achieve power-efficient incoherent (spontaneous- rather than stimulated-emission-based) light sources. The reduced radiative lifetime has the benefit of increasing the efficiency of even poor emitters and allowing for faster source modulation. Another important benefit of MDM waveguides is that they only support a single propagating mode for sufficiently small metal-to-metal spacings. As a result, a large fraction of energy is naturally directed into this well-defined mode. In more conventional sources, energy is lost through coupling to undesired modes. The existence of this preferential decay channel in turn enables improved photon management downstream from the source, as excellent couplers already exist to connect these single-mode MDM waveguides to low-loss dielectric waveguides[10], as shown schematically in Fig. 2.

High-confinement waveguide sources constitute an exciting new class of chip-scale devices that combine efficient charge injection and facile photon extraction. The experiments discussed by Walters and colleagues constitute a significant step forward in the realization of ultracompact sources on a silicon platform. By presenting an elegant implementation of an electrically pumped, plasmon-enhanced light source, the work also serves as a source of new inspiration for the design of truly nanoscale photonic devices and circuits. ❐

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CELL RHEOLOGY

Stressed-out stem cells

Experiments have shown that the physical characteristics of the matrix surrounding a stem cell can affect its behaviour. This picture gets further complicated by studies of stem cells and their differentiated counterparts that show that the cells' own softness also has a clear role in how they respond to stress.

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Embryonic stem cells (ESCs) have recently garnered significant interest owing to their ability to develop — or 'differentiate' — into many different mature cell types and their resulting potential use in regenerative therapies. To effectively control embryonic stem cells for such applications, soluble chemical growth factors have been used to maintain their immature state or cause them to develop into mature cell types. However, mounting evidence indicates that the cell's surrounding environment, which in the body is composed of proteins that assemble into a network called the extracellular matrix, can regulate how the cell matures. Outside the body, passive matrix properties such as stiffness[1],