PLASMONIC CIRCUITS

Detecting unseen light

The electrical detection of surface plasmons in nanowires by a micrometre-sized detector brings the possibility of compact photonic circuits closer.

Luis Martin-Moreno

Photonic circuits have the potential to be faster and to have larger bandwidth than their electronic counterparts. But they face the problem that light is difficult to confine in regions smaller than one wavelength. A tentative solution is the use of metals, which support tightly bound electromagnetic modes known as surface plasmons (SPs). Usually, plasmonic systems are optically excited and either probed by complex near-field techniques or, after being coupled back into light, analysed by far-field measurements. It would, however, be highly desirable to both launch and detect SPs by electrical means, both for plasmonic circuits[1] acting on their own, or for their integration with conventional electronic circuits. Abram Falk and co-workers, reporting on page 475 of this issue[2], present a new configuration that brings this goal a step closer by demonstrating an all-electrical, micrometre-sized SP detector.

Falk and co-workers' device consists of two crossing nanowires, each with a diameter of the order of 100 nm and a few micrometres in length. One of the nanowires is made of silver and supports SPs running along the nanowire axis. The other is made of germanium, which is bonded to metallic pads and acts as a field-effect transistor. The working principle of the device is that an SP, guided along the Ag nanowire to the Ag–Ge region, excites electron–hole pairs that give rise to a detectable current between the metallic pads.

Falk *et al.* provide three important results. The first is that SPs running along the Ag nanowire can actually be detected electrically. For this, the current is measured while the area containing the device is raster scanned by a focused laser beam. As expected, direct illumination of the Ge nanowire creates an electrical current. By contrast, illumination of the Ag nanowire generates a non-negligible current along the Ge nanowire only when performed at the end points. This indicates that SPs are being excited and detected; experiments based on optical detection schemes[3,4] have shown that only illumination of the metallic nanowire end-points excites SPs. This is because propagating electromagnetic waves cannot excite bound SPs due to momentum mismatch. At the end points, the rapid spatial variation of the nanowire geometry provides the missing momentum.

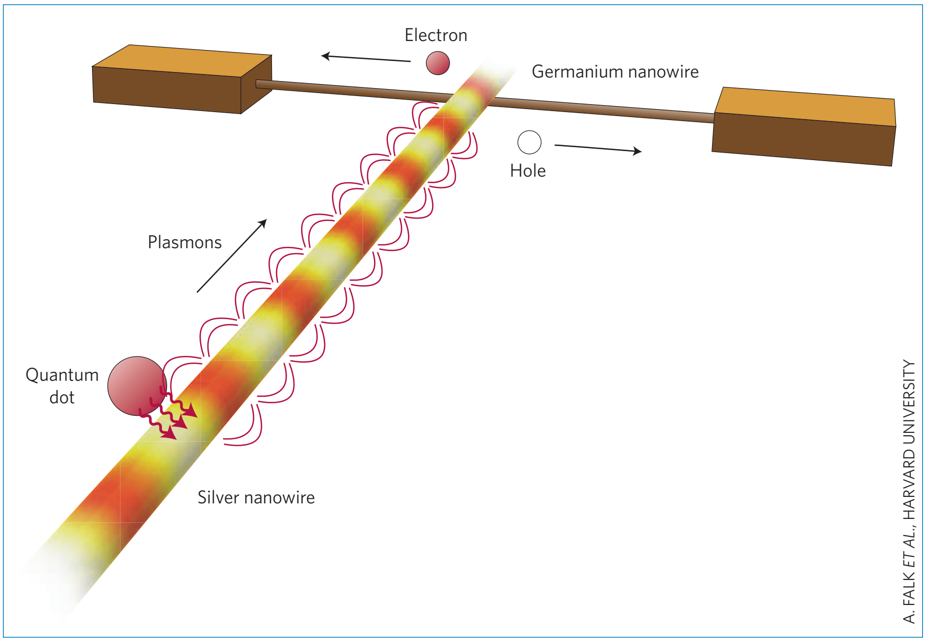

Figure 1 | Schematic representation of a Ag nanowire, acting as a launching pad for SPs and a crossing Ge nanowire, which supports an electrical current whenever electron–hole pairs are excited by the SP electric field at the Ag–Ge contact. In the scheme, SPs are created by the de-excitation of a QD.

Furthermore, the current is larger when the polarization of the laser points along the Ag nanowire axis, which is consistent with the excitation of the fundamental SP mode. Although this mode is mainly radial, it has a small electric-field component along the wire axis, leading to an effective axial dipole moment[5].

Electrical detection of SPs has previously been achieved for particle plasmons[6] and SPs on a flat interface[7]. However, the quasi-one-dimensional geometry considered by Falk *et al.* is more suitable for subwavelength integrated circuits. Moreover, its potential for local detection could be used for imaging purposes if the system were to be mounted on a scanning tip.

The second main result is that the generated current can be amplified by a factor of a few hundred by applying a bias voltage to the metallic pads — this increases the collection efficiency of the electron–hole pairs generated by the SP.

Finally, the near-field SP detector was used to electrically detect the emission from a single-photon emitter. For this, the device was covered by a thin dielectric layer containing a dilute concentration of quantum dots (QDs). Optical excitation of the QDs allowed the recording of their position. Simultaneously, the current was measured and showed a maximum when the frequency of the incident beam matched the excitation frequency of the QDs. Importantly, only QDs near the Ag nanowire were able to induce a current above the noise level, ruling out the possibility that the Ge nanowire was directly absorbing the radiation. Instead, the results are consistent with de-excitation of the QD close to the Ag nanowire primarily through the large local density of electromagnetic modes induced by the

SPs[8], and the transport of these SPs to the Ge detector.

The analysis of the far-field fluorescence from individual QDs or from a cluster of QDs revealed that, in some cases, there is a time lapse between two consecutive photon detections. This property, known as 'photon antibunching', is characteristic of single-photon emitters, which require a finite re-excitation time after photon emission. Thus, in accordance with previous work[9], the authors suggest that these QDs also act as single-plasmon sources. However, up to now, the existence of single plasmons has been based on indirect measurements made on photons. An intriguing possibility could be to test the quantum nature of SPs through the noise spectrum of the induced electrical current — just as the sound of rain falling on a roof gives us information on the discreteness and size of water drops.

It must be noted that in the device presented by Falk *et al.*, the existence of an electrical current relies on asymmetries in the directions defined by the arms of the Ge nanowire with respect to the Ag nanowire axis. A cylindrically symmetric SP cannot excite electrons in a symmetric wire crossing at 90° because the SP electric field points to the left at the left-hand arm of the detector, and to the right at the right-hand arm. The existence of a substrate does not break this left–right symmetry. The asymmetry in the reported study was largely uncontrolled, although it depended on the bias voltage applied between the metal pads; it would therefore be beneficial in the future to have a method of controlling and optimizing the coupling between the Ag and Ge nanowires.

Although the present work represents another step in the direction of an electrically and locally addressable plasmonic circuit, the excitation of the SPs still relies on optical methods. The combination of the present proposal with existing devices for the electrical excitation of SPs[10] (or, perhaps, using as an emitter a nanowire made from a direct bandgap semiconductor or a p–n structure) could finally create the much-sought-after 'dark' optical circuits in the nanoscale region. ❐

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OPTOMECHANICS

Photons refrigerating phonons

Optomechanics is a promising route towards the observation of quantum effects in relatively large structures. Three papers, each discussing a different implementation, now combine optical sideband and cryogenic cooling to refrigerate mechanical resonators to fewer than 60 phonons.

Andrew Cleland

Quantum mechanics provokes much popular interest, due to its highly non-intuitive predictions and its unsettling contradictions of everyday experience. Ironically, quantum mechanics has never really been needed to understand mechanical systems. This is because mechanical systems are typically dominated by thermal effects, which destroy the coherence that distinguishes quantum behaviour. Over the past two decades it has become apparent that it should be possible to reach the quantum limit for some mechanical systems[1], driven by developments in nanoelectromechanical systems[2–4], and more recently in optomechanics, in which light is coupled to a mechanical system, enabling use of the full panoply of optical control techniques[5].

The experimental focus is on mechanical resonators, with resonance frequencies f_M typically between a few kilohertz and a few hundred megahertz. Cooling to the quantum ground state, which is one way to reach the quantum limit, requires reduction of the resonator's thermal energy k_BT to below the energy quantum hf_M. At 1 kHz, this requires temperatures below an astounding 50 nK, whereas at 100 MHz this requires $T < 5$ mK. Conventional cryogenic techniques can be used to lower the resonator's physical temperature towards these values, but typically further reduction is needed, especially for the lower resonator frequencies.

There are a number of optical techniques that can be used to cool a mechanical mode — similar to those used to cool the motion of atoms. One way is to parametrically couple the mechanical resonator to an optical cavity, with optical frequency f_O. The parametric coupling is achieved by construction; for example, the optical cavity can be formed by placing two mirrors so that they face one another, and trapping light between them. One of the mirrors is made very small, and placed on the mechanical resonator, so that the mechanical motion changes the spacing of the mirrors and thus changes the optical cavity's resonance frequency (Fig. 1). By trapping light in the optical cavity, the mechanical motion of the resonator can be cooled by the radiation pressure of the photons trapped in the cavity. This type of radiation pressure damping has been successfully demonstrated[6,7], but the minimum mechanical energy is ultimately limited by the quantum uncertainty of the energy ΔE in the cavity, related to the cavity's optical lifetime τ (the average time a photon is trapped in the cavity) by $\Delta E \sim h/\tau$. If the cavity lifetime is too short, this prevents cooling of the mechanical mode to its quantum ground state.

To cool to the quantum ground state of the resonator, clearly the cavity's optical lifetime needs to be large; if the lifetime can be made to satisfy $\tau f_M >> 1$, meaning that a photon will stay in the cavity much longer than the oscillation period of the resonator, one can operate in the resolved-sideband limit of the resonator–cavity system. The minimum achievable resonator energy is then well below the energy quantum hf_M; that is, the resonator can in