Near-field Electrical Detection of Optical Plasmons and Single Plasmon Sources

Frank H. L. Koppens[1,4], Abram L. Falk[1], Chun L. Yu[2], Kibum Kang[3], Nathalie de Leon Snapp[2], Alexey V. Akimov[1], Moon-Ho Jo[3], Mikhail D. Lukin[1], and Hongkun Park[1,2]

[1]Department of Physics and [2]Department of Chemistry and Chemical Biology, Harvard University, 12 Oxford Street, Cambridge, MA 02138, USA. [3]Department of Materials Science and Engineering, Pohang University of Science and Technology, San 31, Hyoja-Dong, Nam-Gu, Pohang, Gyungbuk, 790-784, Korea

[4]ICFO-Institut de Ciencies Fotoniques, Mediterranean Technology Park, 08860 Castelldefels (Barcelona), Spain

frank.koppens@icfo.es

We demonstrate an efficient nanoscale electrical detector for propagating surface plasmons, an essential component for integrated plasmonic nanocircuits. Our technique is based on the near-field coupling between guided plasmons and a nanowire field-effect transistor. We demonstrate that this near-field circuit can efficiently detect the plasmon emission from a single quantum dot that is directly coupled to the plasmonic waveguide.

Photonic circuits can be much faster than their electronic counterparts, but they are difficult to miniaturize below the optical wavelength scale. Nanoscale photonic circuits based on surface plasmon polaritons (SPs) are a promising solution to this problem because they can localize light below the diffraction limit. However, there is a general tradeoff between the localization of an SP and the efficiency with which it can be detected with conventional far-field optics. Here we describe a new all-electrical SP detection technique based on the near-field coupling between guided plasmons and a nanowire field-effect transistor (Fig. 1a,b) [1]. The Ag NW guides SPs to the Ag/Ge junction, where they are converted to electron-hole (e-h) pairs [2-4] and detected as current through the Ge NW. The Ag NWs are highly crystalline and defect-free, allowing SPs to propagate over distances of several microns without scattering into free-space photons.

Electrical plasmon detection is demonstrated by scanning a focused laser beam across an Ag/Ge crossbar device and recording the current (I) through the Ge NW as a function of the diffraction-limited laser spot position. These data, recorded at zero bias voltage (V_b), show that current flows through the Ge NW only when the laser beam is focused on four distinct spots on the device (Fig. 1b). First, current is detected when the laser is focused near the Ag/Ge junction, due to the direct photoresponse of the Ge NW [5]. The photocurrent induced on the left (I_{left}) and right (I_{right}) sides of the junction have opposite signs (discussed below). Moreover, current through the Ge NW (I_{plas}) is recorded when the laser is focused at either end of the Ag NW. This I_{plas} signal is the key signature for electrical SP detection. Propagating SPs can be launched in the Ag NW only when the excitation laser is incident on the Ag NW ends. Away from the ends, free space photon-to-SP conversion is strongly suppressed by the wave vector mismatch between the two modes. If light scattered off the Ag NW were responsible for the current flowing through the Ge NW, a photocurrent signal would also be detected when the laser is focused on the middle of the Ag NW, in clear contrast to the data shown in Fig. 1b.

An important figure of merit for our detector is the overall plasmon-to-charge conversion efficiency (η), defined as the ratio of detected charges to the number of SPs reaching the Ag/Ge junction. The values of η in our devices typically ranged from 0.01 – 0.1 This efficiency can be tuned by applying a gate voltage (V_{gate}) to an additional electrical contact defined at one end of the Ag NW (data not shown).

These results can be understood by considering electrical plasmon detection as a multistep process. First, the AC electric field of the SP generates e-h pairs in the Ge NW via near-field coupling. Second, the DC electric field within the Ge NW separates these e-h pairs into free charges before recombination takes place. The separated *e-h* pairs are then detected as current. The shape of the built-in DC electric potential, a potential well (Fig 1a, inset), can be inferred from the sign of the Ge photocurrent at either side of the Ag/Ge junction. The depth of this well is tuned by V_{gate}. Asymmetric electrical contacts to the Ge can cause the potential well in the Ge to be off center with respect to the Ag NW. This asymmetry explains the difference in magnitude of I_{right} and I_{left}, and determines the sign of the plasmon-induced current. The DC electric field in the Ge NW is nonzero even at $V_b = V_{gate} = 0$, due to charge transfer across the Ag/Ge junction and/or the occupation of surface charge traps.

We demonstrate the utility of our near-field SP detector by electrically detecting emission from a CdSe quantum dot acting as a single plasmon source (Fig. 1c). The tight field confinement around Ag NWs causes a large fraction of the spontaneous emission from nearby emitters (i.e. 30-100 nm away) to be captured as SP modes [6,7]. These SPs are then converted into an electrical signal at a Ge NW detector. Individual quantum dots (QDs) are coupled to an Ag NW by covering an Ag/Ge device with a 30 nm film of poly(methyl methacrylate) containing a dilute concentration of chemically synthesized CdSe QDs. Optical fluorescence measurements (Fig. 1f) show that some QDs are close to the Ag NW. When the laser excites one of these QDs, a current signal in the Ge NW detector is observed (pink circle in Fig. 1c) in addition to optical fluorescence from the QD. The dependence of this signal on the excitation wavelength is a clear proof that the current signal results from QD emission (Fig. 1d). Significantly, photon correlation measurements of the far-field fluorescence (Fig. 1e) demonstrate a clear anti-bunching signature, indicating that this spot corresponds to an individual QD.

Nanoscale near-field SP detection opens up several directions for further research. An electrical SP detector could be mounted on a scanning tip, providing a new SP imaging technique. In conjunction with an electrically driven plasmon source [8], a near-field SP detector could be integrated into a "dark" optoelectronic-plasmonic nanocircuit in which all coupling is in the near field. The plasmon detection sensitivity could be improved by using a nanoscale avalanche photodiode or a superconducting film [9] as the SP detector, enabling efficient electrical detection of individual plasmons. Electrical plasmon detectors could lead to new applications for optical sensing without collection optics, including the measurement of plasmon states whose coupling to the far field is suppressed by symmetry. Finally, the strong near-field coupling between single-plasmon emitters and plasmonic nanocircuits could lead to completely new capabilities that are not available with conventional photonics, such as nonlinear switches, single-photon transistors, and quantum non-demolition detectors.

[1] Near field electrical detection of optical plasmons and single plasmon sources, A. L. Falk, F. H. L. Koppens, C. Yu, K. Kang, N. P. de Leon Snapp, A. V. Akimov, M-H. Jo, M. D. Lukin, H. Park

[2] De Vlaminck, I., Van Dorpe, P., Lagae, L. & Borghs, G. Local electrical detection of single nanoparticle plasmon resonance. Nano Lett. 7, 703-706 (2007).

[3] Mapel, J.K., Singh, M., Baldo, M.A. & Celebi, K. Plasmonic excitation of organic double heterostructure solar cells. Appl. Phys. Lett. 90, 121102 (2007).

[4] Ditlbacher, H. et al. Organic diodes as monolithically integrated surface plasmon polariton detectors. Appl. Phys. Lett. 89, 161101 (2006).

[5] Ahn, Y. & Park, J. Efficient visible light detection using individual Germanium nanowire field effect transistors. Appl. Phys. Lett. 91, 162102 (2007).

[6] Akimov, A.V. et al. Generation of single optical plasmons in metallic nanowires coupled to quantum dots. Nature 450, 402-406 (2007).

[7] Chang, D.E., Sorenson, A.S., Hemmer, P.R. & Lukin, M.D. Strong coupling of single emitters to surface plasmons. Phys Rev. B 76, 035420 (2007).

[8] Koller, D.M. et al. Surface plasmon coupled electroluminescent emission. Appl. Phys. Lett. 92, 103304 (2008).

[9] Heeres, R.W., Dorenbos S.N., Koene, B., Solomon, G.S., Kouwenhoven L.P., Zwiller, V., On-Chip Single Plasmon Detection, Nano Letters, volume 10, Issue 2, Page 661-664, (2010).

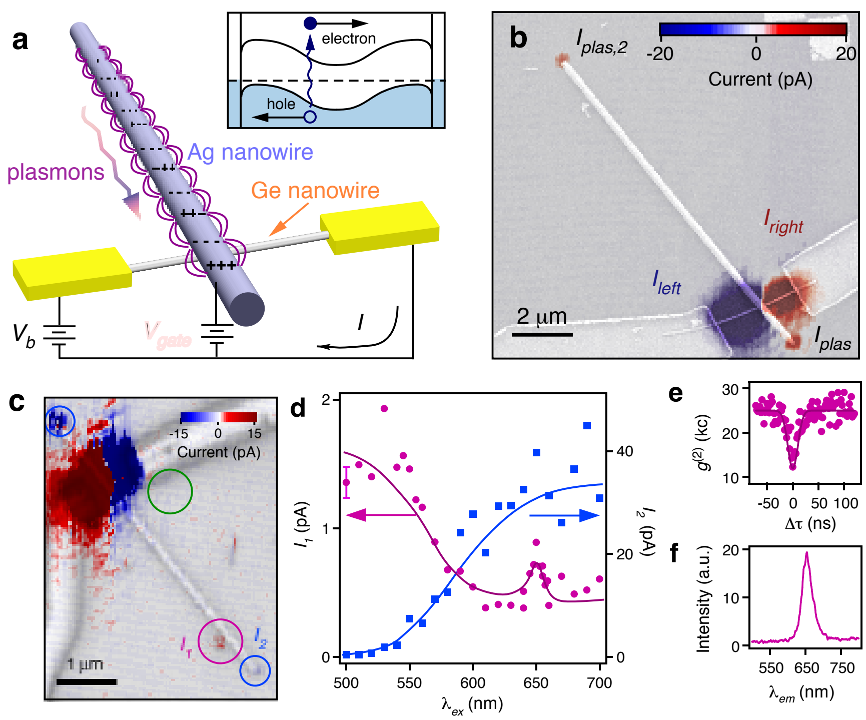

Figure 1. **a.** Schematic of electrical plasmon detector operation. Inset: electron-hole pair generation and separation in the Ge NW detector. **b.** Scanning electron micrograph of Device 1, overlaid with the current through the Ge NW as a function of excitation laser position. Excitation laser power P = 2.0 µW, wavelength λ_{ex} = 532 nm, V_b = 0, V_{gate}=0. **c.** Electrical detection of emission from a single CdSe colloidal QD. I as a function of laser position, overlaying a reflection image of Device 4. P = 1.5 µW, λ_{ex} = 530 nm. V_b = 0, V_{gate} = 0. The violet circle indicates the detector signal corresponding to QD emission into the Ag NW plasmon modes. The blue circles correspond to detection of surface plasmons launched directly by the laser, at the ends of the NW. The green circle corresponds to the position of a QD that is not near the Ag NW, and hence does not generate a current in the detector. **d.** I_1 (QD emission, violet circles) and I_2 (direct laser-to-plasmon signal, blue squares) as a function of λ_{ex}. **e.** Second-order self-correlation function $g^{(2)}(\tau)$ of the QD fluorescence,.The coincidence rate at τ = 0 approaches the 0.5 mark, confirming that a single QD is present. **f.** QD emission spectrum.