Propagating Plasmons on Silver Nanowires

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ABSTRACT

Chemically synthesized Ag nanowires (NWs) can serve as waveguides to support propagating surface plasmons (SPs). By using the propagating SPs on Ag NWs, the surface-enhanced Raman scattering of molecules, located in the nanowire-nanoparticle junction a few microns away from the laser spot on one end of the NW, was excited. The propagating SPs can excite the excitons in quantum dots, and in reverse, the decay of excitons can generate SPs. The direction and polarization of the light emitted through the Ag NW waveguide. The emission polarization depends strongly on the shape of the NW terminals. In branched NW structures, the SPs can be switched between the main NW and the branch NW, by tuning the incident polarization. The light of different wavelength can also be controlled to propagate along different ways. Thus, the branched NW structure can serve as controllable plasmonic router and multiplexer.

1. INTRODUCTION

The life style and economic growth have been deeply changed by the information technology revolution since last middle century. However, as the development of micro-fabrication and integration technologies, the physical limits of the integrated chips, such as quantum size effect and thermal effect have already restrict the advance of the information technology. Photons as a carrier of the information are superior to electrons in bandwidth, density, speed, and dissipation. More over, photons could carry intensity, polarization, phase, and frequency information which could break through the limitation of binary system. But due to the diffraction limit, the photonic components and devices can not be fabricated small enough for large-scale integration. Surface plasmons (SPs) are collective electronic excitations evanescently confined along the interface of a conductor and a dielectric, which offers a promising way to manipulate light at the nanometer scale, even to realize the photonic miniaturization. And the research on SPs has become a rapidly growing field, i.e. Plasmonics [1, 2].

SPs can be used for the manipulation of light intensity [3, 4], polarization [5, 6], propagation [7-11]

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and optical force [12-14] at the nanometer scale. Some pioneer works were to discover the huge electromagnetic field enhancement in the nanogaps between metal nanoparticles [15, 16], which is the foundation for surface-enhanced spectroscopy and some other nonlinear effects. In the recent two years, a few different metal nanostructure systems, including nanohole-nanoparticle [3], nanowire-nanoparticle [4], scanning tunneling microscope (STM) tip-nanoparticle [17], nanorice [18, 19], nanoflowers [20], etc. were investigated

The control of light propagation at the nanometer scale is critical for the development of nanophotonic circuits and novel sensors, and is a hot research topic in the field of Plasmonics all over the world. Recently, the important progresses in the study of SP propagation, which mainly incude ref. [7-11] and will be summarized in this presentation.

2. PROPAGATING SURFACE PLASMONS-MOLECULE/EXCITON INTERACTION

2.1 Remote-excitation surface-enhanced Raman scattering using propagating SPs

In usual surface-enhanced Raman scattering (SERS) measurements, the laser is focused directly on the position where Raman signal will be collected. Whereas, the separation of excitation and detection sites will provide flexibility in specific applications and new scheme design for SERS detection. By employing SPs on Ag NWs, remote-excitation SERS at the single molecule level was achieved. Figure 1 shows a Ag nanowire-nanoparticle system, in which the probe molecules in the nanowire-nanoparticle junction was remotely excited by the laser focused on the left end of the NW. The separation between the excitation and detection sites is a few micorns. It should be mentioned that simultaneous multisite remote-excitation SERS was also achieved in the study.

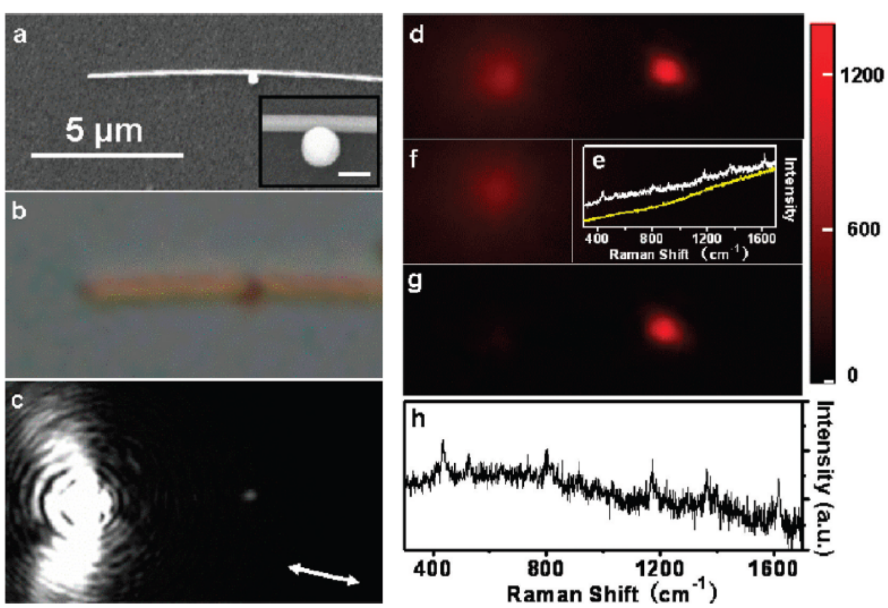

Figure 1: Remote-excitation SERS of MGITC molecules excited through propagating plasmons. (a, b) SEM and white light reflection images of a nanowire-nanoparticle system. (c) Light guide image of the same system by

focusing the 632.8 nm laser light on the left NW end. (d) Raman image obtained at 436 cm-1 Raman peak. (e) Raman spectra from the laser spot at the left end of NW and the remote site of the wire/particle junction, respectively. The remoteexcitation SERS spectrum is obtained by separating the Raman collection spot from the laser spot. (f) The fluorescence background image of smooth ITO glass only. (g) The Raman image after background subtraction of panel f from panel d. (h) The remote-excitation SERS spectrum after fluorescence background correction with the spectra taken from panel e. (reproduced from ref. [7])

The novel technique for performing SERS using propagating SPs as a remote excitation source has remarkable advantages compared with direct optical excitation. Remote-excitation can achieve the illumination within micrometer area, and thus improve the signal to noise ratio and decrease the damage to the samples. This approach allows for remote-excitation SERS sensing and has great potential to expand ultrasensitive chemical detection to new systems. The multisite sensing capability could be very useful in a variety of contexts from probing complex molecular processes in intracellular environments to studying the propagation characteristics of plasmon waves themselves on NWs or other nanoscale structures. It may even be useful for constructing complex plasmonic networks, where the junction between NW and nanoparticle would serve as a node. Such possibilities could greatly expand the use of SPs for local communications and information transfer at submicrometer length scales.

2.2 Propagating SP induced photon emission from quantum dots

The interaction between propagating SPs in silver NWs and excitons generated in quantum dots (QDs) was investigated recently. The propagating SPs can excite excitons, which results in QD emission, as shown in Fig. 2. When the 710 nm wavelength laser light was focused on the bottom end of the NW, bright spots were detected at both the wire kink and the upper tip where the propagating SPs coupled out as photons. Figure 2d shows the wide-field excitation QD emission image, which shows that while there is strong emission of the QDs near the shorter segment of the NW probably due to the higher QD concentration, there is very little QD emission near the longer segment of NW. In Fig. 2e, the QD emission image was acquired with the 710 nm excitation source focused on the bottom NW tip. In this case, while the excitation is at a remote location (the bottom tip of the NW), QD emission can be observed along the NW.

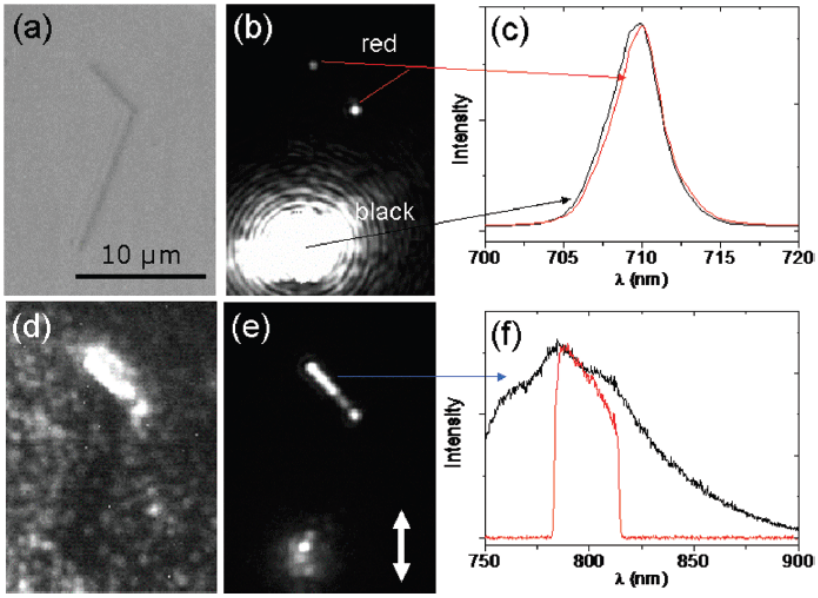

Figure 2: (a) White light transmission image of an Ag NW. (b) Optical image with 710 nm laser focused on the bottom NW tip. (c) Spectra of laser (black) and light coupled out (red). (d) QD emission image with wide-field excitation by a 532 nm laser. (e) Image of QD emission induced by propagating SPs in the Ag NW using an 800/30 nm band-pass filter. The 710 nm laser power is about 200 μW, and exposure time is 5 s. (f) Spectra measured at the bright part of the NW remotely excited in (e) with 750 nm long pass filter (black) and 800/30 nm band-pass filter (red), respectively. Scale bar is the same for all images. The white arrow in (e) indicates the polarization of the 710 nm laser. (reproduced from ref. [8])

The excited QDs can also launch the SPs in the Ag NW, which propagate in the NW and finally couple out at the NW tips (Fig. 3). In Fig. 3b, the wide field excitation QD emission image is shown for the system shown in Fig. 3a. When the 710 nm laser was focused on a spot in the middle of the straight NW (red circle), no light is coupled out at the two ends of the NW, as shown in Fig. 3c. This is consistent with the notion that one cannot launch the SPs directly at this location. Nevertheless, as the laser can excite excitons in QDs at this location, there exists a decay channel for these excitons into propagating SP excitations. Such exciton-SP conversion can be seen in Fig. 3d. The direct excitation leads to QD emission at the focused spot while the exciton-SP conversion is reflected by the photon emission at two ends of the NW.

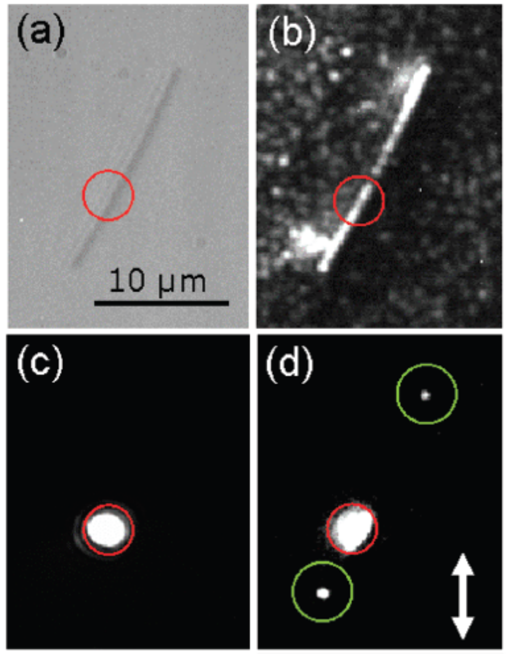

Figure 3: (a) White light transmission image of an Ag NW. (b) QD emission image with wide-field excitation. (c) The image with 710 nm laser focused on the position marked with a red circle as in (a) and (b). (d) Emission image acquired using an 800/30 nm band-pass filter and with an excitation wavelength of 710 nm. The laser is focused on the same position as in (c) but with a higher power level of 200 μW. The exposure time is 5 s. The white arrow indicates the polarization of the laser. (reproduced from ref. [8])

3. PROPERTIES OF PROPAGATING SURFACE PLASMONS

3.1 Directional Light Emission from Propagating SPs of Ag NWs

While intensive experimental and theoretical efforts have focused on improving the in-coupling efficiency of light, and on how to reduce the propagation loss, relatively little is known about their light-emitting properties. This is critically important information for the design and development of SP waveguides in integrated photonic or electronic devices and systems. The spatial distribution of the light emitted from one end of a NW following the excitation of SPs at the other end was measured. The light from the end of the NW is found to be emitted in a cone of angles peaking at nominally 45-60° from the NW axis, with virtually no light emitted along the direction of the NW (Fig. 4). The angular distribution of the light emission is found to be relatively independent of the shape and length of the wire and can be understood using a simple model invoking the Fabry-Pérot resonances of the NW waveguide. This strongly angular-dependent emission is a critical property that must be considered when designing coupled NW-based photonic devices and systems.

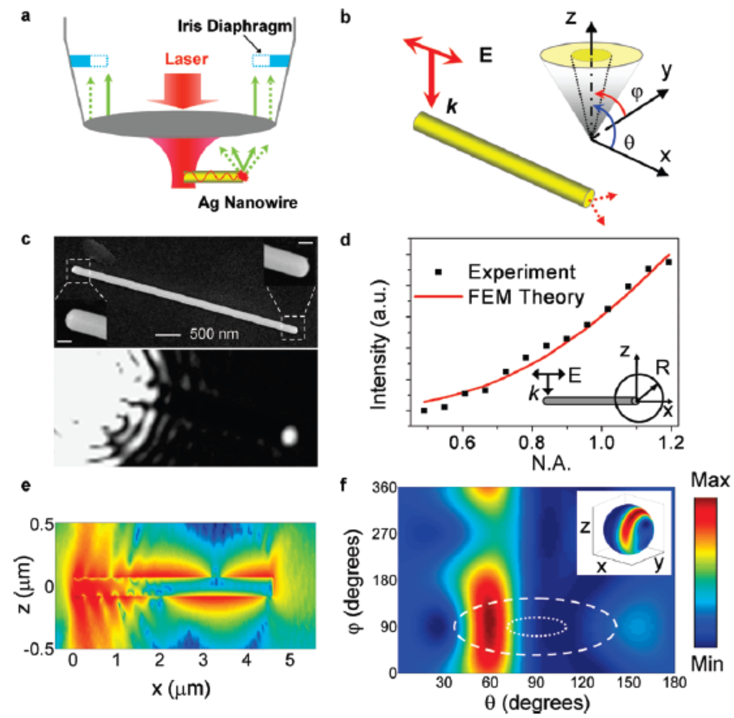

Figure 4: Angular emission measurement. (a) Scheme of the measurement. The excitation and collection by an objective (Olympus UPlanApo, 100×, oil immersion n) 1.518). The iris diaphragm inside the objective varies the N.A. from 1.2 to 0.5 during the measurements. (b) The coordinates referred to in the experiments. The wave vector and polarization of the incident light are represented by the red arrows. The different N.A. corresponds to different opening angles of the collection cone. The light that is emitted into the cone will be collected by the objective and recorded by the CCD. (c) The SEM image of a wire of length 4.6 μm and diameter 158 nm, and its optical image in a microscope under the excitation of a 633 nm laser spot polarized along the wire. The scale bar in the SEM insets showing the wire end are 100 nm. (d) The measured emission intensity as a function of the N.A. of the objective (black squares). Red curve is the integrated far-field intensity for different N.A. obtained from the simulation. (e) The FEM calculated distribution of the Poynting intensity around the wire. (f) The calculated emission intensity as a function of angles φ and θ obtained by far-field transformation. The inset shows the corresponding angular distribution on the integration sphere. The white rings of different sizes are the emission angles that can be collected by the objective for N.A.) 1.2 and 0.5, respectively. (reproduced from ref. [9])

3.2 Correlation between Incident and Emission Polarization in Ag NW waveguides

Polarization is another important property of light, but very little is known about how the polarization of the out-coupled light in a plasmonic waveguide is related to the polarization of the incident light. The correlation between incident and emission polarizations in Ag NW waveguides was investigated by varying the polarization of the excitation beam and analyzing the polarization of the light emitted at the other end of the NW. The polarization change is found to depend sensitively on the geometrical shape of the wire terminations. Theoretical analysis shows that the shape of the NW termination where the SP is launched determines the relative intensity of the SPs modes excited in the NW, which can modify the polarization of the emitted light. The shape of the emission end, on the other hand, can change both the spatial distribution and polarization of the emitted light. Because of the mode-specific damping lengths of the SPs, the properties of the emission polarization can depend on the wire diameter and for long wires, the wire length. With properly designed NW terminations, a NW can serve either as a polarization maintaining plasmonic waveguide or as a nanoscale polarization rotater. Figure 5 shows a NW, in which the emission polarization is kept the same as the exciation polarization.

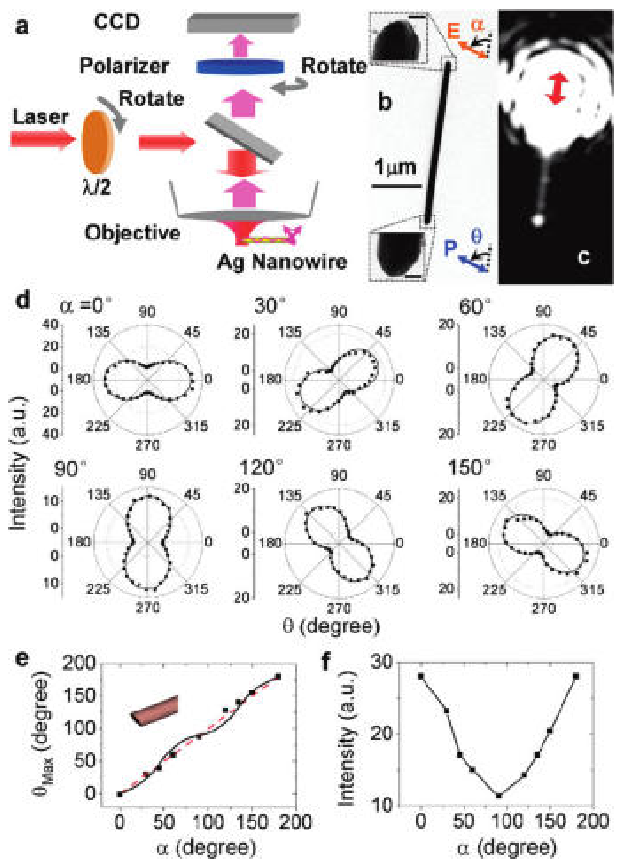

Figure 5: Polarization measurement. (a) Scheme of the experiment. (b) TEM image of a wire of length 3.36 μm and diameter 130 nm. The scale bar in the TEM insets showing the shape of the wire ends is 50 nm. (c) Optical image of the NW in a microscope under the excitation of a 633 nm laser spot polarized along the wire. Red arrow indicates the polarization of the laser. (d) Emission intensity as a function of the polarizer rotation angle θ, for different incident polarizations (R) 0, 30, 60, 90°, 120, and 150°, respectively). The incident polarization and the polarizer are rotated anticlockwise relative to the wire axis, which is defined by the angle R and θ in the inset of (b). (e) Polarization of the emission as a function of the incident polarization. θmax is the polarization angle of the emission defined as the rotation angle of the polarizer when the emission is the maximum. Dots are the measured data. Black curve is the simulation result based on a cylindrical wire with the shape of both ends shown in the inset. The linear dashed red line is drawn to guide the eyes. (f) Maximum

emission intensity from the wire as a function of incident polarization angle. (reproduced from ref. [10])

3.3 Branched Silver NWs as Controllable Plasmon Routers

SPs propagation in branched Ag NW system was investigated. The propagating SPs were found to be routed into different wire branches and result in light emission from the corresponding wire ends by controlling the polarization of the incident laser light, which means a branched NW structure can serve as a controllable plasmonic router. Besides, this routing behavior is found to be strongly dependent on the wavelength of light. Thus for certain incident polarizations, light of different wavelength will be routed into different branches without interfering. Figure 6 show the routing behavior of a branched NW structure for 632. nm and 785 nm light. So the branched NW can also serve as a multiplexer in integrated plasmonic circuits. This finding may have numerous applications in future nanophotonic devices, circuits, and networks.

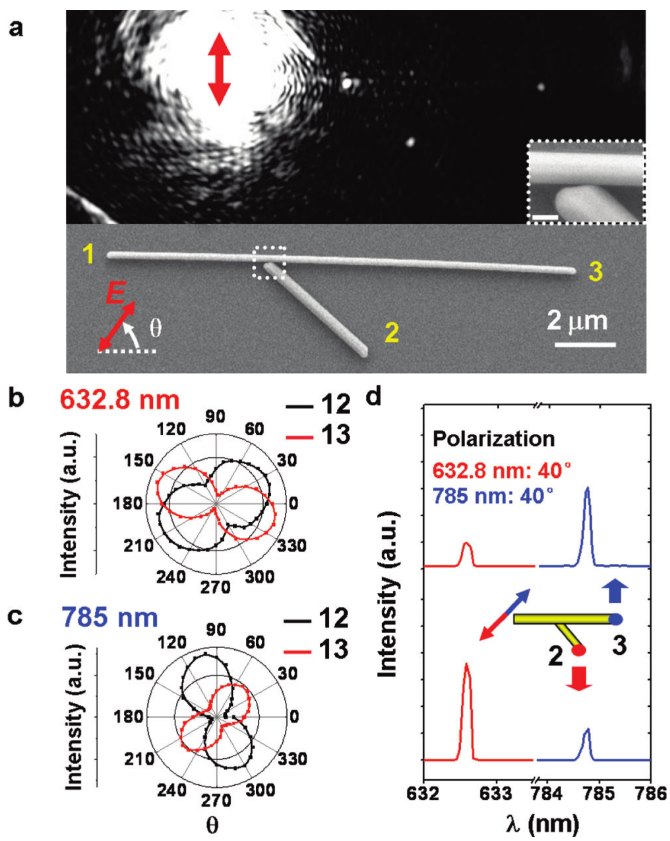

Figure 6: (a) Optical image of a silver nanobranch excited by a 633 nm wavelength laser. The red arrow represents the incident polarization. The inset is the SEM image of the nanobranch and the junction, where the scale bars are 2 μm and 200 nm, respectively. θ is the rotation angle of the incident polarization. (b,c) Emission intensity from branch ends 2 (black) and 3 (red) as a function of incident polarization angle for 633 and 785 nm wavelength excitation, respectively. (d) The spectra collected from wire end 2 (upper curves) and 3 (lower curves). The polarization of the incident light is 40°. (reproduced from ref. [11])

SUMMARY

By using the propagating SPs on Ag NWs, remote-excitation SERS was achieved and the bidirectional interaction of SPs and excitons in QDs are studied. The light coupled out at the end of the NW is emitted in the direction of 45-60° from the direction of the wire, and the emission polarization depends strongly on the shape of the NW terminals. By controlling the incident polarization, branched NW structure can serve as plasmonic router and multiplexer.

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