AIP Applied Physics Letters

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Citation: Appl. Phys. Lett. **97**, 161110 (2010); doi: 10.1063/1.3503534
View online: http://dx.doi.org/10.1063/1.3503534
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v97/i16
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Surface plasmon coupling to nanoscale Schottky-type electrical detectors

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(Received 12 August 2010; accepted 24 September 2010; published online 21 October 2010)

We have investigated the near-field coupling of surface plasmons to a titanium/CdS nanowire interface for two different device configurations. A bare aluminum grating on an underlying aluminum layer exhibited the expected stronger electrical signal for perpendicular versus parallel light polarization. An opposite intensity ratio was detected when the grating and the Schottky contact are connected via an aluminum–silica–aluminum sandwich structure. Based upon finite difference time domain device simulations, the enhanced coupling for parallel polarization is attributed to the emergence of a transversal electric wave within the metal–insulator–metal structure. © *2010 American Institute of Physics*. [doi:10.1063/1.3503534]

While the confinement of light is diffraction limited, surface plasmons allow the confinement of optical fields to strongly subwavelength dimensions. Such a confinement is necessary to achieve highly integrated optical components,[1,2] as well as to integrate them into electrical circuitry.[3] Most passive plasmonic components such as waveguides,[4] resonators,[5] couplers,[6] or interferometers[7] can already be routinely realized at a microscopic scale. More challenging is the efficient microscopic excitation and detection of surface plasmons. The combination of these two components would enable to directly exploit the optical near-field within very compact device configurations, and hence to further approach plasmonics-based integrated optical circuits. Thus far, the direct, microscopic launching of surface plasmons has been realized by using the leakage of organic light emitting diodes[8] or by plasmonic lasers.[9] Moreover, electrical plasmon detection has been achieved with the aid of germanium,[10] III–V semiconductors,[11] organic semiconductors,[12] and superconductors.[13]

In the present work, we explore the electrical detection of surface plasmon polaritons (SPPs) by guiding them to the Schottky contact of an individual cadmium sulphide (CdS) nanowire (NW). CdS is a widely used II–VI semiconductor [band gap 2.5 eV (Ref. 14)] that is well-suited for photodetector applications.[15] CdS NWs are advantageous for the present task since they are electrically conductive only under photoillumination (dark currents are in the range of picoamperes).[16]

Figure 1(a) shows an optical reflection image of an investigated device. The cross section of the device along the dashed line is schematically depicted in Fig. 1(b). The drawing illustrates how surface plasmons launched at the grating propagate along the metal stripe until they intersect with the CdS NW. The NW lies on top of the aluminum and forms a Schottky contact with a titanium electrode. The electrical near-field of the SPP excites electron-hole pairs in the CdS wire, which are separated by the built-in electric field close to the contact. This device configuration effectively combines the advantageous properties of both, aluminum and titanium. Specifically, aluminum allows for efficient SPP propagation at high optical frequencies [propagation length $L_{Al}(\lambda=488\ \text{nm})\approx 10\ \mu\text{m}$], albeit it forms high resistive electrical contacts to CdS. Titanium, by contrast, yields good Schottky contacts (work function 4.3 eV)[17] on CdS but is a poor plasmonic waveguide [$L_{Ti}(\lambda=488\ \text{nm})\approx 1\ \mu\text{m}$].

The devices were fabricated by consecutive e-beam lithography steps. The dimensions of the grating, with a spacing of 265 nm, a width of 216 nm, and a height of 80 nm, have been adapted to the used materials and laser wavelength.[18] Due to the limited laser spot size of the 50× air objective (NA=0.8), the number of aluminum ridges in the grating has been restricted to three. The CdS NWs with diameters in the range of 50–100 nm were synthesized by a solvothermal method[19] and spin-coated onto the Si substrate coated with a 300 nm thermal oxide layer. Prior to the evapo-

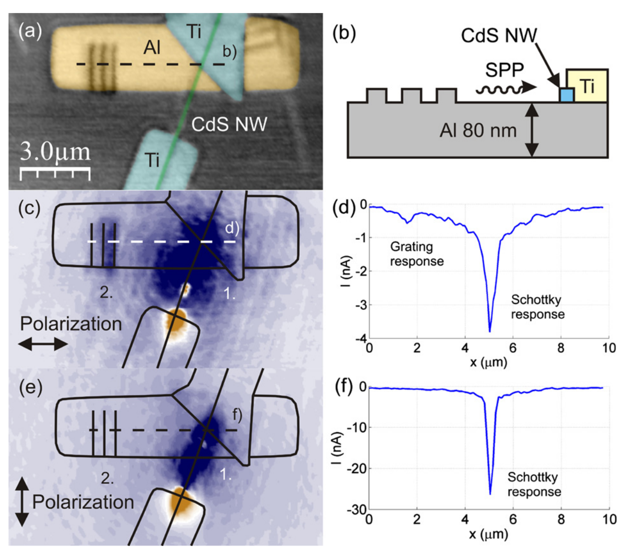

FIG. 1. (Color online) (a) Reflection image and (b) corresponding schematic cross section of a typical device. The Ti electrodes and CdS NWs are colored to increase their visibility. Panels (c) and (e) show the photocurrent maps of the same device for respective light polarization perpendicular and parallel to the grating. The dashed lines in panels (c) and (e) correspond to the current profiles (d) and (f), respectively.

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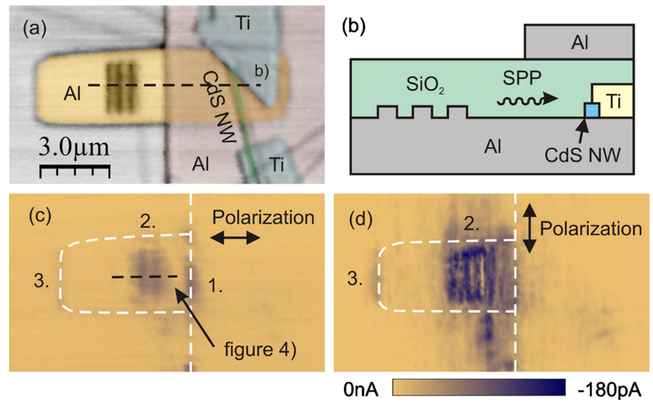

FIG. 2. (Color online) (a) Colored reflection image and (b) corresponding schematic cross section of an Al-capped device. The panels (c) and (d) show the photocurrent map for light polarization perpendicular and parallel to the grating.

ration of 100 nm titanium, the contact areas on the CdS NWs were exposed to an argon-plasma for 2 min in order to achieve local n-type doping.[19] The completed devices were characterized under ambient conditions by scanning photocurrent microscopy (SPCM),[20] using a laser wavelength of 488 nm.

Figures 1(c) and 1(e) display photocurrent maps recorded on the device in Fig. 1(a) with light polarization perpendicular and parallel to the grating, respectively. The current profiles in Figs. 1(d) and 1(f) are taken along the corresponding dashed lines in panel (c) and (e). Both maps exhibit two major signals, one at the contacts (1) and the other at the grating (2). The strong signal at the titanium electrodes originates from the direct illumination of the Schottky contact. It shows pronounced polarization dependence, with maximum magnitude for light polarization parallel to the NW long axis.[21] Simulations of CdS NWs on an aluminum surface reveal their optical absorption to differ by a factor of ~9 between the two polarization directions (see Ref. 27). This difference agrees well with the sevenfold to eightfold larger signal in case of the parallel light polarization. The second photoresponse in Fig. 1(c) at the grating can be attributed to surface plasmons, as supported by its polarization dependence. If the incident light is polarized perpendicular to the ridges a photoresponse appears at the grating [Fig. 1(c)] which vanishes for parallel polarized light [Fig. 1(e)]. This is expected for a plasmonic coupler.[22] In the photocurrent profile of Fig. 1(d) the plasmon response can be distinguished, although it overlaps with the spatial decaying signal of the Schottky contact.

To better distinguish the plasmon response from stray light at the NW contact, the device structure was modified by capping the Schottky contact by a thick metal layer, as can be discerned from Fig. 2(a) and the corresponding cross-section in Fig. 2(b). To this end, a 200 nm thick layer of SiO_2 was evaporated onto the whole substrate, and a restricted area around the Schottky contact selectively covered by another 80 nm layer of aluminum. This resulted in a metal–insulator–metal (MIM) structure which prevents direct illumination of the contact but does not hinder the propagation of plasmonic transversal magnetic (TM) waves. Figures 2(c) and 2(d) depict the photocurrent maps of such a device, acquired with perpendicular and parallel light polarization, respectively. For polarization perpendicular to the ridges [Fig. 2(c)], three photoresponses at different locations can be distinguished. The first signal occurs at the edge of the top metal layer, which can also excite modes inside the MIM structure. The second one is due to surface plasmons launched at the grating. The shape of the two separate peaks in the photo response will be discussed further below. A third signal emerges at the left outer edge of the aluminum stripe. At this aluminum/substrate interface, a plasmon is launched which does not intersect directly with the CdS NW, and therefore results in only a very weak signal. In case of light polarization parallel to the grating [Fig. 2(d)], the photoresponse unexpectedly doubles in size. It furthermore changes its shape, leading to a broad photoresponse everywhere in the vicinity of the MIM structure, with some minima at the grating position. At the same time, no separate contribution from the edge of the top metal layer can be observed.

Valuable clues regarding the origin of the detected polarization dependence could be gained from finite difference time domain simulations of the devices. Two-dimensional calculations were performed using the MEEP software package (see Oskooi *et al.*[23] and Mathewson *et al.*[24] for optical constants of aluminum), with the light source modeled by a Gaussian field distribution with a full width at half maximum of 450 nm. The calculated electric field distribution for both polarization directions is shown in Fig. 3, where the bold black features represent the aluminum layers and the grating. For a MIM mode to be excited by a surface plasmon [see Fig. 3(a)], the light source must be polarized perpendicular to the grating (E_x component, not shown here). Such a mode corresponds to a TM-wave comprising E_x, E_y, and H_z components. Of these, the major field component E_y is plotted in Fig. 3(a), in which the propagating wave in the MIM structure can be clearly seen. Conversely, for light polarization parallel to the grating, one would expect no plasmon propagation since surface plasmons only exist as TM-waves[25] and a light source polarized in E_z cannot [in two-dimensional (2D)] couple to a TM mode. Hence, the MIM mode in Fig. 3(b) must be directly excited corresponding to a transversal electric (TE) wave (H_x, H_y, E_z). As reported by Dionne *et al.*,[4] it is possible to excite TE-waves in MIM structures at short enough wavelengths (<600 nm). The dispersion relation of such a mode crosses the light line, such that no grating is needed to achieve a k-vector matching. Consequently, any scattered light with polarization in the E_z direction that reaches the MIM structure can easily couple to the TE mode. Standard multilayer eigenmode calculations revealed the existence of an excitable TE mode with a propagation length of around 3.5 μm for the given device structure. Even though this mode is strongly damped, it is absorbed more strongly by the CdS NW, since the E_z component lies in the plane of the NW. This mechanism is also operative for the device in Fig. 1, and explains the higher photocurrent observed for

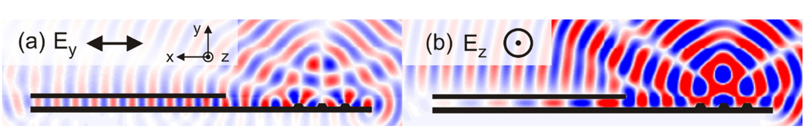

FIG. 3. (Color online) 2D color plots of the (a) E_y component of a TM-wave (source polarized in E_x) and (b) E_z component of a TE-wave (source polarized in E_z).

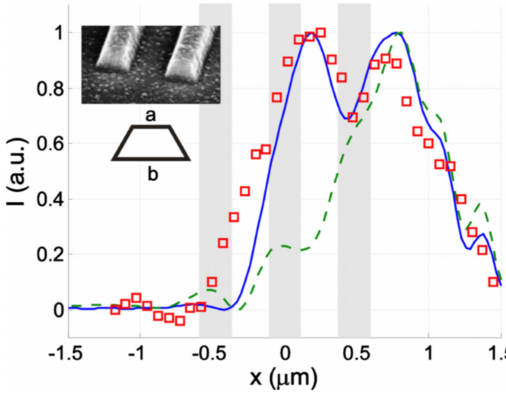

FIG. 4. (Color online) Normalized photocurrent plotted as a function of position of the illuminating beam for light polarization perpendicular to the grating. The dashed curve corresponds to a grating with rectangular shaped ridges, the solid to trapezoid like shaped ridges, and the squares are data points along the current profile marked in Fig. 2(c). The grey bars in the background denote the positions of the three ridges of the grating. The inset shows a scanning electron microscope image of two ridges of the grating.

parallel polarization in this case [cf. Fig. 2(d)].

To further elucidate the coupling mechanism, the plasmonic light flux was calculated as a function of the source position, thus simulating the SPCM measurements. In previous experiments wherein light was focused on single ridges, the maximal coupling efficiency was found to be centered over the single ridge.[26] The situation is different for the present devices, since the launched plasmons can be detected only in one direction, whereby the coupling maximum is shifted to one side. In Fig. 4, the computed data is compared to the normalized, measured data for light polarization perpendicular to the grating (for parallel polarization see the Ref. 27). While the profile obtained for perfect rectangular ridges exhibits its maximum on the right side where the detector is located, it is unable to account for the left maximum in the measured photocurrent [red squares, taken from the profile in Fig. 2(c)]. Significantly better agreement is achieved by incorporating a trapezoid shape of the ridges (a/b ratio of ~ 0.6), which is apparent from scanning electron microscope images of the grating (see inset of Fig. 4). It is known from previous studies (see Radko *et al.*[18]) that the shape of the ridges and the arrangement of the grating can significantly alter the coupling efficiency to surface plasmons. The trapezoid shape originates from metal deposited on the side walls of the Poly(methyl methacrylate) resist during the evaporation of the grating.

The plasmon detection sensitivity can be enhanced by applying an electrical bias to the CdS NW. While at zero bias only excitons in the vicinity of the metal contact are separated and contribute to the photocurrent, under an external bias φ the depletion zone width $x(\varphi)=\sqrt{2\varepsilon\varepsilon_0|\varphi|ne}$ is increased (with n as the charge carrier density, e the elementary charge, and ε the dielectric constant of CdS). This in turn leads to a larger area of absorbed photons, and a concomitant decrease in the charge carrier recombination rate. As a consequence, a moderate bias of 0.5 V is sufficient to increase the photocurrent by three orders of magnitude. Such enhancement is particularly effective for devices with a metal cover layer, as without this top layer the direct photoresponse of the Schottky contact becomes too dominant and hence obscures any other signal.

In summary, the presented Schottky-type devices comprising an individual CdS NW are useful local electrical detectors for surface plasmons. In principle they can be realized by standard optical lithography enabling simple and compact plasmonic experiments. The polarization dependence of the generated photocurrents can be well explained by the TE waves confined within the MIM structure that serves to avoid the dominant direct illumination response of the Schottky contact. Similar detector devices with controllable width of the Schottky barrier might enable probing the spatial distribution of the plasmon near-fields.[27]

This work was supported by the Bundesministerium für Bildung und Forschung (BMBF) within the framework of the SONAPOLY project.

[1]W. L. Barnes, A. Dereux, and T. W. Ebbesen, Nature (London) **424**, 824 (2003).
[2]R. Zia, J. A. Schuller, A. Chandran, and M. L. Brongersma, Mater. Today **9**, 20 (2006).
[3]J. A. Dionne, K. Diest, L. A. Sweatlock, and H. A. Atwater, Nano Lett. **9**, 897 (2009).
[4]J. A. Dionne, H. J. Lezec, and H. A. Atwater, Nano Lett. **6**, 1928 (2006).
[5]L. Douillard, F. Charra, and Z. Korczak, Nano Lett. **8**, 935 (2008).
[6]M. Hochberg, T. B. Jones, C. Walker, and A. Scherer, Opt. Express **12**, 5481 (2004).
[7]H. Ditlbacher, J. R. Krenn, N. Felidj, B. Lamprecht, G. Schider, M. Salerno, A. Leitner, and F. R. Aussenegg, Appl. Phys. Lett. **80**, 404 (2002).
[8]D. M. Koller, A. Hohenau, H. Ditlbacher, N. Galler, F. Reil, F. R. Aussenegg, A. Leitner, E. J. W. List, and J. R. Krenn, Nat. Photonics **2**, 684 (2008).
[9]R. F. Oulton, V. J. Sorger, T. Zentgraf, R. M. Ma, C. Gladden, L. Dai, G. Bartal, and X. Zhang, Nature (London) **461**, 629 (2009).
[10]A. L. Falk, F. H. L. Koppens, C. L. Yu, K. Kang, N. L. Snapp, A. V. Akimov, M. Jo, M. D. Lukin, and H. Park, Nat. Phys. **5**, 475 (2009).
[11]P. Neutens, P. V. Dorpe, I. Vlaminck, L. Lagae, and G. Borghs, Nat. Photonics **3**, 283 (2009).
[12]H. Ditlbacher, F. R. Aussenegg, J. R. Krenn, B. Lamprecht, G. Jakopic, and G. Leising, Appl. Phys. Lett. **89**, 161101 (2006).
[13]R. W. Heeres, S. N. Dorenbos, B. Koene, G. S. Solomon, L. P. Kouwenhoven, and V. Zwiller, Nano Lett. **10**, 661 (2010).
[14]S. Ninomiya and S. Adachi, J. Appl. Phys. **78**, 1183 (1995).
[15]C. Soci, A. Zhang, X. Y. Bao, H. Kim, Y. Lo, and D. Wang, J. Nanosci. Nanotechnol. **10**, 1430 (2010).
[16]Y. Gu, E. S. Kwak, J. L. Lensch, J. E. Allen, T. W. Odom, and L. J. Lauhon, Appl. Phys. Lett. **87**, 043111 (2005).
[17]*CRC Handbook of Chemistry and Physics*, edited by D. R. Lide (CRC, London, 2008).
[18]I. P. Radko, S. I. Bozhevolnyi, G. Brucoli, L. Martín-Moreno, F. J. García-Vidal, and A. Boltasseva, Phys. Rev. B **78**, 115115 (2008).
[19]T. Dufaux, J. Boettcher, M. Burghard, and K. Kern, Small **6**, 1868 (2010).
[20]K. Balasubramanian, M. Burghard, K. Kern, M. Scolari, and A. Mews, Nano Lett. **5**, 507 (2005).
[21]J. Wang, M. S. Gudiksen, X. Duan, Y. Cui, and C. M. Lieber, Science **293**, 1455 (2001).
[22]H. L. Offerhaus, B. van den Bergen, M. Escalante, F. B. Segerink, J. P. Korterik, and N. F. van Hulst, Nano Lett. **5**, 2144 (2005).
[23]A. F. Oskooi, D. Roundy, M. Ibanescu, P. Bermel, J. D. Joannopoulos, and S. G. Johnson, Comput. Phys. Commun. **181**, 687 (2010).
[24]A. G. Mathewson and H. P. Myers, Phys. Scr. **4**, 291 (1971).
[25]S. A. Maier, *Plasmonics* (Springer, New York, 2007).
[26]H. Ditlbacher, J. R. Krenn, A. Hohenau, A. Leitner, and F. R. Aussenegg, Appl. Phys. Lett. **83**, 3665 (2003).
[27]See supplementary material at http://dx.doi.org/10.1063/1.3503534 for calculations of gratings illuminated at parallel polarization and for the polarization dependent absorption of CdS NWs.