Towards surface-plasmon generation by electrical injection at telecom wavelengths with a semiconductor device

D. Costantini, A. Bousseksou, **R. Colombelli**
Institut d'Electronique Fondamentale
Univ. Paris Sud et CNRS, UMR8622
91405 Orsay, France

L.Greusard, R. Rungsawang, Y. De Wilde
Institut Langevin
ESPCI ParisTech, CNRS UMR 7587
75231 Paris Cedex 05, France.

A. Accard, J. Decobert, G-H. Duan
Alcatel-Thales III-V Lab,
route de Nozay, 91461 Marcoussis cedex, France.

T. Zhang, S. Callard
Institut des Nanotechnologies de Lyon
Site Ecole Centrale de Lyon
36 Avenue Guy de Collongue, 69134 Ecully, France

***Abstract*— We propose and demonstrate a strategy to electrically generate surface-plasmons (SP) in the telecom range. The core idea is that properly designed semiconductor laser active regions might compensate the large losses that SPs experience in the telecom wavelength range. We show that laser devices based on tensile-strained semiconductor quantum wells - hence emitting transverse magnetic polarized light - are suitable for plasmon generation *via* electrical injection. Experimental evidence is obtained using near-field microscopy measurements.**

Surface Plasmon Polariton, generation, electrical injection

I. Introduction

Several surface plasmon polariton (SPP) passive components have been demonstrated to date, showing attractive performances for extreme light confinement and high bandwidth modulation [1,2]. On the other hand, the lack of a viable technology to compensate the large optical losses, typical of SPPs, partly limits practical applications. As a matter of fact, efforts have been recently devoted to the development of active SPP devices, for the their generation, amplification [3] and stimulated emission [4,5]

II. A Semiconductor-based approach

We propose a semiconductor active region which enables plasmonic active devices in the telecom wavelength range. Plasmonic devices based on planar architectures typically require transverse magnetic (TM) polarized light. To satisfy this requirement at λ=1.3-1.55 µm our choice fell on diode lasers based on tensile-strained InGaAlAs semiconductor quantum wells, which operate in TM polarization as demonstrated in Ref. [6]. Furthermore, this semiconductor gain medium is compatible with electrical injection (end-fire coupling architectures can be implemented relatively easily, as Ref. [7] shows for longer, mid-infrared wavelengths). This characteristic represents an advantage for practical uses and for device integration.

In this work, we build on the previous demonstration of mid-infrared (λ=7.5 µm) SPP generation with a compact semiconductor device [8]. Integrated SPPs generation is obtained by coupling a laser source with a plasmonic waveguide *via* a judiciously designed coupler grating section which compensate for the missing momentum. In order to transfer the concept at short telecom wavelengths, we have performed in-depth numerical analysis to study and maximize the coupling efficiency by playing on the device parameters [9] (Fig. 1).

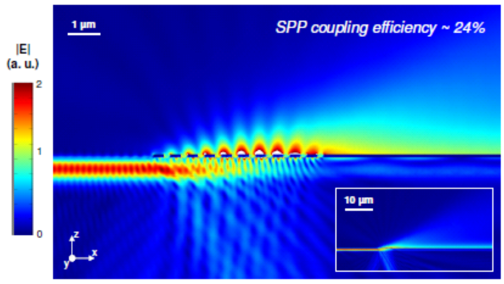

Fig.1. Finite element simulation presenting the absolute value of the electric field in the coupler design. The waveguided mode (injected from the left) is efficiently converted into a plasmonic mode (propagating towards the right).

We have then experimentally elucidated the effect of the proximity of the metallic contacts to the device active region [10]. This is a crucial ingredient: in order to efficiently couple the laser light with the propagating SPPs it is necessary to enhance the interaction between the metal and the waveguided mode. In turn, this enhanced interaction leads to increased waveguide losses. We have identified and experimentally developed a structure which represents an optimal trade off between coupling efficiency and optical loss. As a second step, we have realized 1st-order metallic DFB lasers, which constitute one of the building blocks of the SPP generator. Figure 2 shows the correct device behavior, with a single mode emission that correctly tunes (from λ=1288 to 1322 nm) with the grating period. Note: the laser development allowed us to experimentally measure the differential gains which can be expressed by this active cores. They are in the hundreds of cm^{-1}/kA. These extremely high values are promising in view of developing loss-compensated metallic meta-structures, or even semiconductor-based spasers.

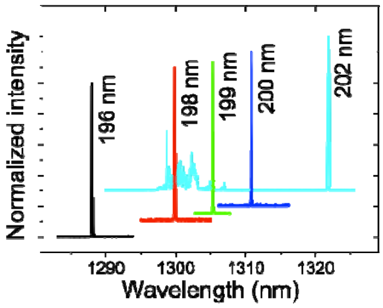

Fig. 2 Single mode emission for five different periods of the DFB grating (from p=196nm to p=202nm).

Finally, we demonstrate SPP generation by providing the *electrically-pumped* version of the slit-doublet experiment [11] in the near-field (Fig. 3). Two coupler gratings and a central passive plasmonic waveguide are placed between two identical DFBs, which act as laser sources. Counter-propagating SPPs are injected by the couplers – as schematized in Fig. 3a - and plasmonic standing waves appear on the central passive section. The SPP generation by electrical injection is demonstrated in Fig 3c, which shows the noteworthy result of transmission SNOM measurements on the surface of the passive waveguide section. In order to detect beyond any doubt the presence of plasmonic waves in the near field, we will present NSOM measurements performed with two additional approaches: aperture less scattering-NSOM, and fiber-based near-field microscopy.

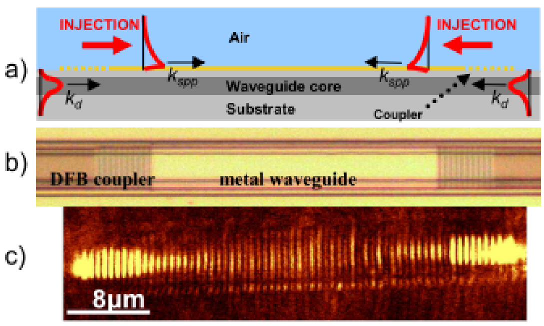

Fig3. a) Schematic (lateral view) of the SPP generator device. Red curves represent the absolute value of the electric field of the laser and the SPP mode. b) Optical image (top view) of the SPP generator device. c) Near field measurement of the passive waveguide surface. Oscillations of the plasmonic standing wave on the passive metallic waveguide are clearly visible.

In the final part of the talk we will discuss a topic which can be of interest for device applications, i.e. the reduction of plasmonic ohmic losses *via* the sole patterning of the top metal layer, and initial results will be presented. We will also discuss the perspective which this integrated approach - based on semiconductor active cores - opens up for the development of electrically pumped semiconductor spasers (Surface Plasmon Amplification by Stimulated Emission of Radiation).

[1] T. W. Ebbesen, C. Genet, and S. I. Bozhevolnyi, "Surface plasmon circuitry," *Phys. Today,* vol. **61**, issue 5, pp. 44, 2008.

[2] D.Gramotnev and S. I. Bozhevolnyi, "Plasmonics beyond the diffraction limit," *Nat. Phot*., vol **4**, pp. 83, 2010.

[3] P. Berini and I. De Leon, "Surface plasmon–polariton amplifiers and lasers" *Nat. Phot*., vol **6**, pp 16–24, 2012.

[4] M. T. Hill, M. Marell, E. S. Leong, B. Smalbrugge, and C.-Z. Ning, "Lasing in metal-insulator-metal sub-wavelength plasmonic waveguides" Opt. Exp., vol 17, no 13, pp.11107, 2009.

[5] S.-H. Kwon, J.-H. Kang, C. Seassal, S.-K. Kim, P. Regreny, Y.-H. Lee, C.M. Lieber, and H.-G. Park, " Subwavelength Plasmonic Lasing from a semiconductor nanodisk with silver nanopan cavity", Nano Lett. 10, 3679 (2010)

[6] J. Decobert, N. Lagay, C. Cuisin, B. Dagens, B. Thedrez, and F. Laruelle, "MOVPE growth of AlGaInAs–InP highly tensile-strained MQWs for 1.3 mm low threshold lasers," Journal of Crystal Growth, vol. **272**, pp. 543, 2004.

[7] J.-P. Tetienne, A. Bousseksou, D. Costantini, R. Colombelli, A. Babuty, I. Moldovan-Doyen, Y. De Wilde, C. Sirtori, G. Beaudoin, L. Largeau, O. Mauguin and I. Sagnes, "Injection of midinfrared surface plasmon polaritons with an integrated device," *App. Phys. Lett*., vol **97**, pp. 211110, 2010.

[8] A.Babuty, A. Bousseksou, J.-P. Tetienne, I. Moldovan Doyen, C. Sirtori, G. Beaudoin, I. Sagnes, Y. De Wilde, and R. Colombelli, "Semiconductor Surface Plasmon Sources," *Phys. Rev. Lett*., vol. **104**, pp. 226806, 2010.

[9] J.-P. Tetienne, A. Bousseksou, D. Costantini, Y. De Wilde, and R. Colombelli, " Design of an integrated coupler for the electrical generation of surface plasmon polaritons", Opt Exp., vol. **19**, no. 19, pp. 18155-18163, 2011.

[10] D. Costantini, A. Bousseksou, M. Fevrier, B. Dagens, R. Colombelli, "Loss and gain measurements of tensile-strained quantum well diode lasers for plasmonic devices at telecom wavelengths", IEEE, Journal of Quantum Electronics, vol **48**, pp. 73. 2012.

[11] L Aigouy, P. Lalanne and J. P. Hugonin, G. Julie and V. Mathet, M. Mortier " Near-Field Analysis of SurfaceWaves Launched at Nanoslit Apertures", *Phys. Rev. Lett***,**vol **98**, 153902, 2007.