Project no.
STRP 016881 SPANS

Project acronym
SPANS

Project title
Single Particle Nanophotonic Switches
(bridging electron microscopy and photonics)

Instrument: SPECIFIC TARGETED RESEARCH PROJECT

Thematic Priority: NMP

Final Publishable Executive Summary

Due date of deliverable: October 31, 2009
Actual submission date: November 30

Start date of project: May 1, 2006 Duration: 42 months

Organisation name of lead contractor for this deliverable:
Consejo Superior de Investigaciones Científicas (CSIC)

Dissemination Level: PP Revision: 1

The main scientific objective of this STREP was to study underlying physical mechanisms of optical switching based upon single-particle phase transitions triggered by light or electron beam excitation and to investigate feasibility of constructing new types of **nano-photonics switches** based on this principle. If successful this project was supposed to provide a **new paradigm for optical data processing** with potential impact in telecommunications and computation technologies by large-scale assembly of such switches in new photonic circuits and will play key roles in other technologies such intelligent high-resolution imaging systems and new **artificially engineered metamaterials** with properties not available in nature.
The second equally important objective of this STREP was to develop **new techniques to study nanophotonic structures** by combining nano-photonic with electron microscopies. Alongside with simple scanning electron imaging providing resolution below the nanometer (far better than conventional scanning near-field optical microscopy), we intended to employ techniques such as cathodeluminescence (CL, equivalently designed as Electron Induced Radiation Emission, EIRE) and electron energy loss spectroscopy (EELS) to determine optical properties of photonic and plasmonic structures.

During the last 42 months of the project, the following tasks have been addressed, according to the workplan:

WP1. Sample fabrication
- Task 1 - Design and construction of vacuum growth chamber with atomic beam source and cryostat.
- Task 2 - Development of electronics for control of the growth process and temperature conditions in the chamber.
- Task 3 - Design of fiberized optical diagnostic equipment for nanoparticle growth and its integration with the growth chamber.
- Task 4 – Development of the growth process for Ga nanoparticles on fiber tip with simultaneous in situ control of their optical properties.
- Task 5 – Development of simultaneous optical and SEM in situ characterization of the samples.
- Task 6 – Development of theoretical platform for comparative analysis of optical and SEM data for the sake of identification of structural phases in nanoparticles.

WP2. Optical characterization
- Task 1 – Design and development of a fully fiberized pump-probe optical diagnostic spectrometer for the experiment of light-induced phase transition in nanoparticles.
- Task 2 – Development of the transient modulators and detection electronics to allow for time-resolved measurements with the above.
- Task 3 – Study of optical properties of metallic nanoparticles on a tip.
- Task 4 – Study of optically-induced phase transitions in nanoparticles.
- Task 5 – Development of theory of optically-induced phase equilibrium in nanoparticles.

WP3. Electron microscopy
- Task 1 – Characterization of the optical properties of the nanoparticles by EELS.
- Task 2 – Test the new specimen holders produced in WP5 to extract induced light.
- Task 3 – Characterization of the optical properties of the nanoparticles by induced light emission.
- Task 4 – Introduced laser radiation into the sample holder via the optical fibre.

WP4. Prove of concept of optical switch
- Task 1 – Design and implementation of optical set up for probing and testing switching characteristic.
- Task 2 – Theoretical analysis and simulation of performance.
- Task 3 – Analysis of use of this concept in nanophotonic devices

WP5. Prove of concept of EIRE
- Task 1 – Design and construction of sample holder at room temperature.
- Task 2 -Optimization of the geometry of the sample holder based upon simulations of EELS and EIRE.
- Taks 3 – Sample holder extended to allow for temperature control.
- Task 4 – Theory and software development to assist the interpretation of EIRE

WP6. Project management
- Task 1 – Construction and maintenance of web site.
- Task 2 – Interim reports, activity and management reports, final report, mid-term report, audits.
- Task 3 – Analysis of intellectual property issues and contact with potential industrial developers.

The task in WP6 not having been addressed in its whole is:
Task 4 – Topical meeting organization
The reasons will be discussed below in details, but are directly linked to the major illness of the CSIC coordinator.

All workpackages have progressed according to the workplan and have been completed with the exception of one deliverable (D6.7 Topical meeting, see below). In addition to this due completion, the consortium of SPANS has demonstrated a blossoming effort in the field of electron-beam nanophotonics, leading to additional unexpected applications of the SPANS project's electron microscopy and numerical simulation tools.

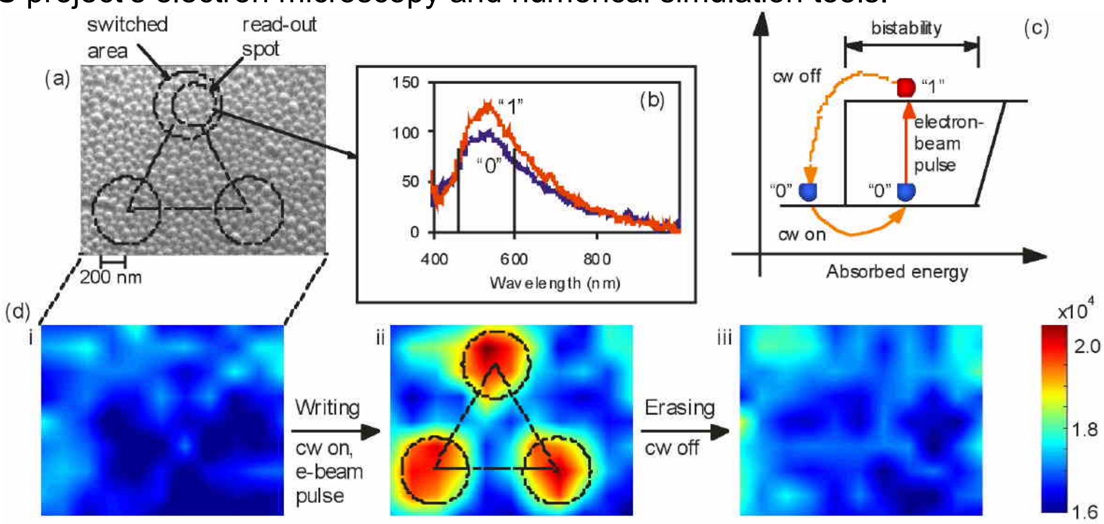

Figure 1: Selective electron-beam-induced writing and EIRE readout of memory elements in a gallium nanoparticle monolayer: (a) Ga nanoparticles of mean diameter 53 nm; (b) Typical EIRE spectra for particles in states '0' and '1'; (c) Schematic temperature hysteresis particle optical properties, illustrating the volatile mode of phase-change memory; (d) EIRE scans showing total intensity between 450 and 600nm from the sample area shown in (a) at different stages of the memory cycle: [i] entire monolayer in state '0', [ii] after electron-beam-induced switching of selected memory elements to state '1', [iii] after erasing the switched elements (restoring them to the '0' state).

Experimental effort by partners 2 and 3, and theoretical efforts of partner 1 have resulted in
(1) Demonstration of new concepts for nanoparticle optical switch/memory (Figure 1),
(2) Design of new instrumentation, including new forms of detectors and ad-hoc scanning electronic, with capabilities for independent or simultaneous EIRE, EELS, and EEGS recording. This has lead to pioneering works, for example, in plasmons mapping with EIRE and EELS (see Figure 2 and Figure 3).
(3) Demonstration of the use of EIRE for optical switching measurement (Figure 1).
(4) Development of several simulation tools for EIRE, EELS and EEGS modeling (Figure 2).
(5) A theoretical proof of concept of the EEGS spectroscopy (see Figure 4) plus the development of the related experimental set-up.

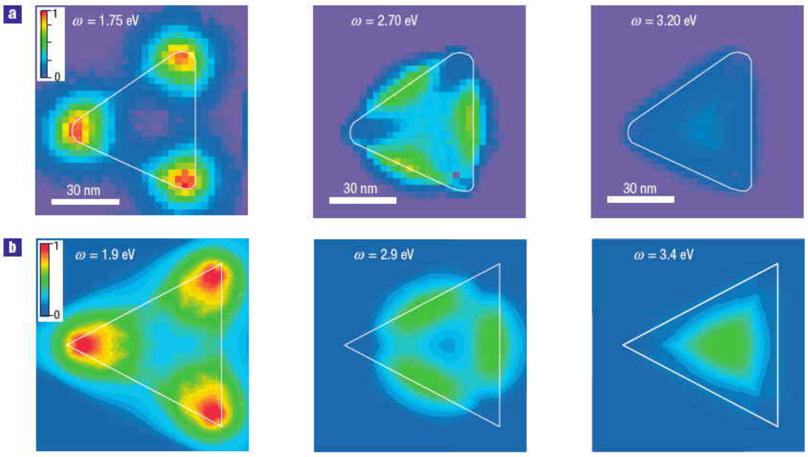

Figure 2: Experimental and simulated EELS amplitude maps for a silver nanoprism. a, Distribution of the modes centred at 1.75, 2.70 and 3.20 eV respectively. The outer contour of the particle, deduced from its HAADF image, is shown as a white line. The colour scale, common to the three maps, is linear and in arbitrary units. b, Simulated amplitude maps of the three main resonances resolved in the simulated EEL spectra of the nanoprism with 78-nm-long sides. The colour linear scale, in arbitrary units, is common to the three maps. The simulated amplitude distributions for the different modes qualitatively match the experimental ones in a.

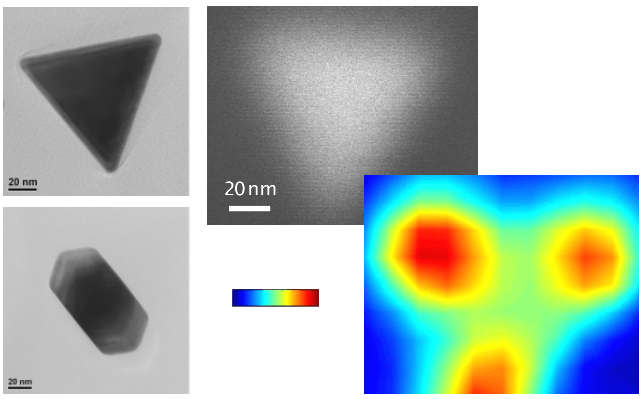

Figure 3: TEM, SEM and EIRE mapping images of a gold nano-prism, wherein the latter reveals the plasmonic mode structure of the particle.

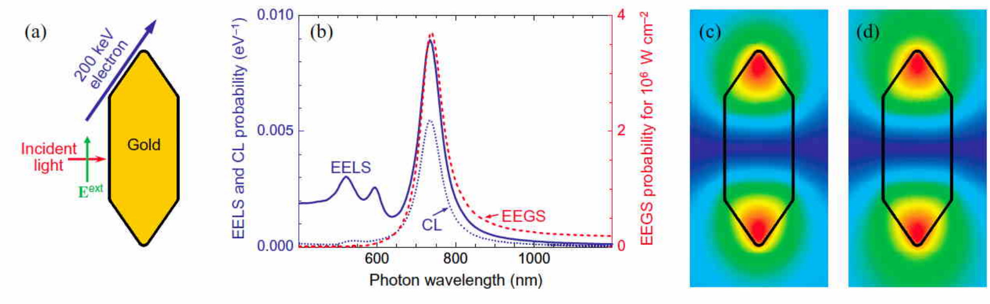

Figure 4: (a) Sketch of electron passing near a nanorod with acute tips illuminated by light polarized parallel to the particle long axis. (b) Comparison of EELS, CL, and EEGS probabilities for the geometry depicted in (a). The EEGS probability corresponds to an illumination intensity of 10^6W cm^{-2}. The distance between the electron trajectory and the gold surface is 1.7 nm. (c) Plasmon map constructed from the EELS probability by scanning the electron beam perpendicularly with respect to the rod axis. (d) Plasmon map obtained from EEGS with the external illumination as shown in (a), and the electron beam perpendicular to the plane of the figure.

Building substantially on the techniques and concepts developed within SPANS, the consortium has performed several EELS and EIRE mapping (on different types of plasmonic nanoparticles) with unrivalled spatial resolution (see e.g. Figure 5). Combined EELS and EIRE experiments have been performed for the first time (see Figure 6). Also, the spectral mapping techniques have been extended to additional systems such as metamaterials, novel electron-beam-pumped nanoscale light sources (see Figure 7) and quantum semi-conducting nanowires (Figure 8).

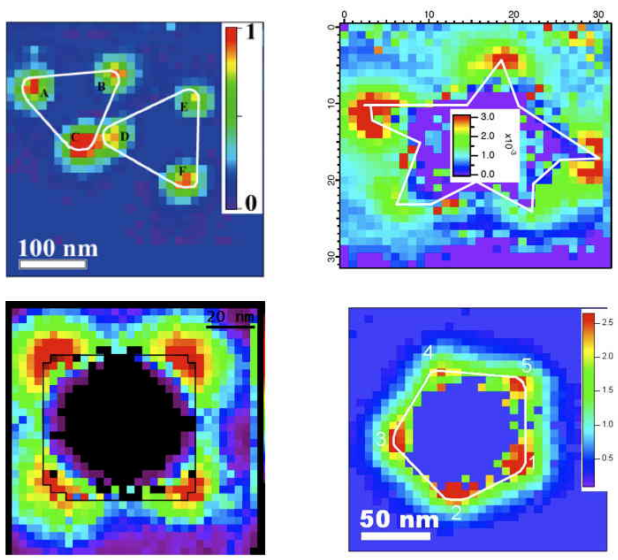

Figure 5: EELS spectral imaging of various structures studied during SPANS (the white or black lines outline the shape as deduced from the inline HAADF). Represented are EELS amplitude maps. Top, left: Coupled silver triangular platelets. Top, Right: gold nanostars (image width is 120 nm). Bottom, left: 60 nm thick silver cube. Bottom, right: Gold decahedra.

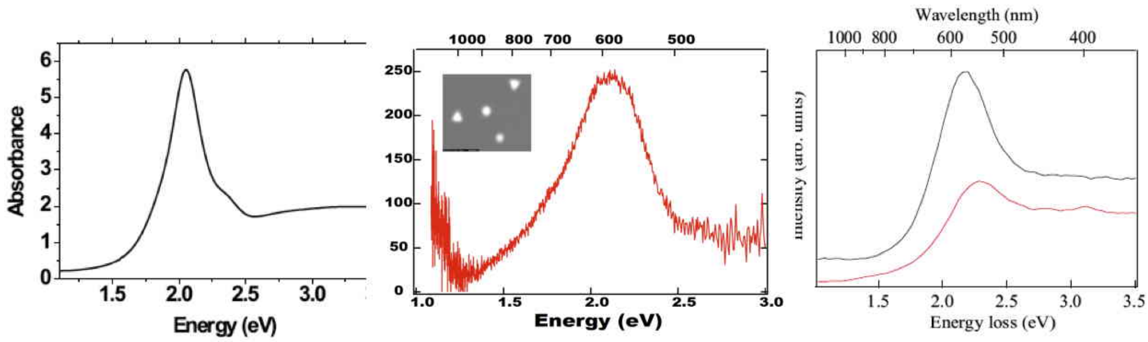

Figure 6: From left to right: Optical absorption, EIRE signal and EELS signal of gold decahedra

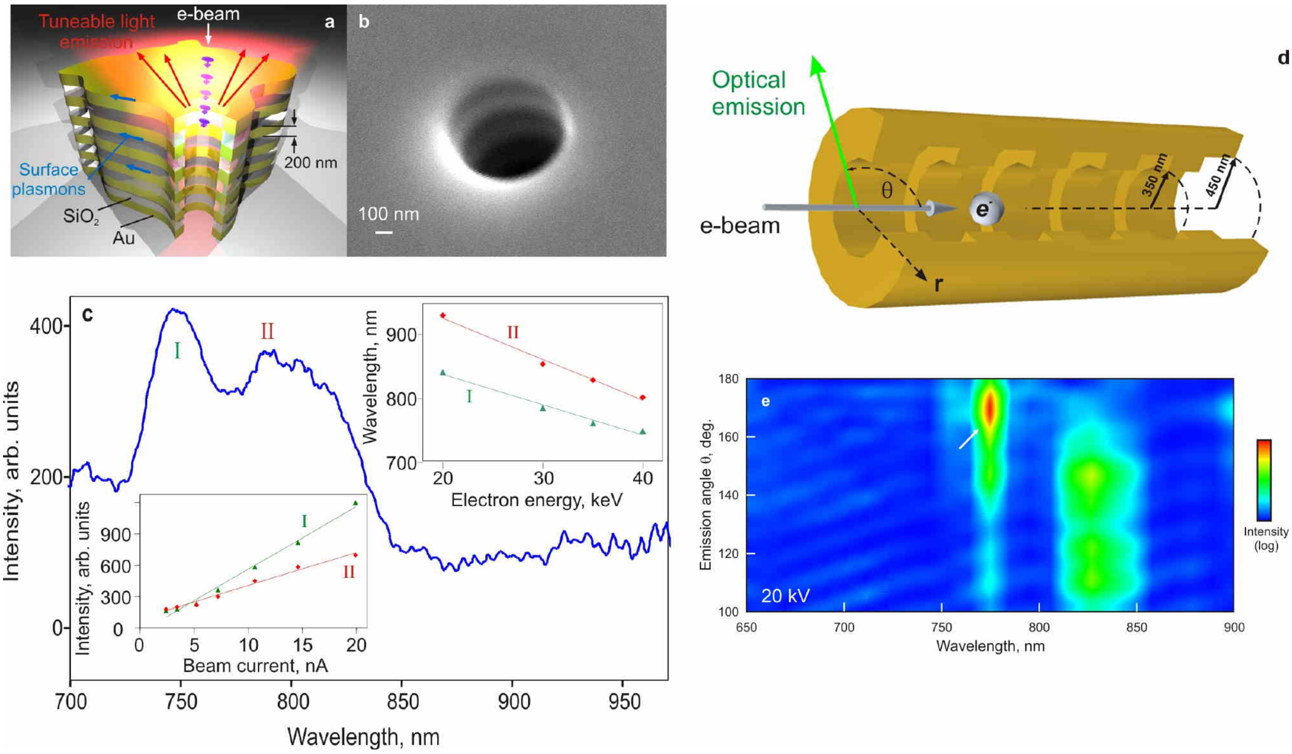

Figure 7: (a) Artist's impression of a light-well: Light is emitted as electrons are launched into a nano-hole through a metal-dielectric multilayer structure; (b) SEM image of a gold-silica light-well; (c) Emission spectrum from a 750 nm diameter well pumped by 40 keV electrons. The upper right inset shows the spectral position of peaks I and II as a function of electron energy. The lower left inset shows the emission intensity into each peaks as a function of electron beam current; (d) Light-well structure modelled using the boundary element method; (e) Calculated Emission probability as a function of wavelength and emission angle.

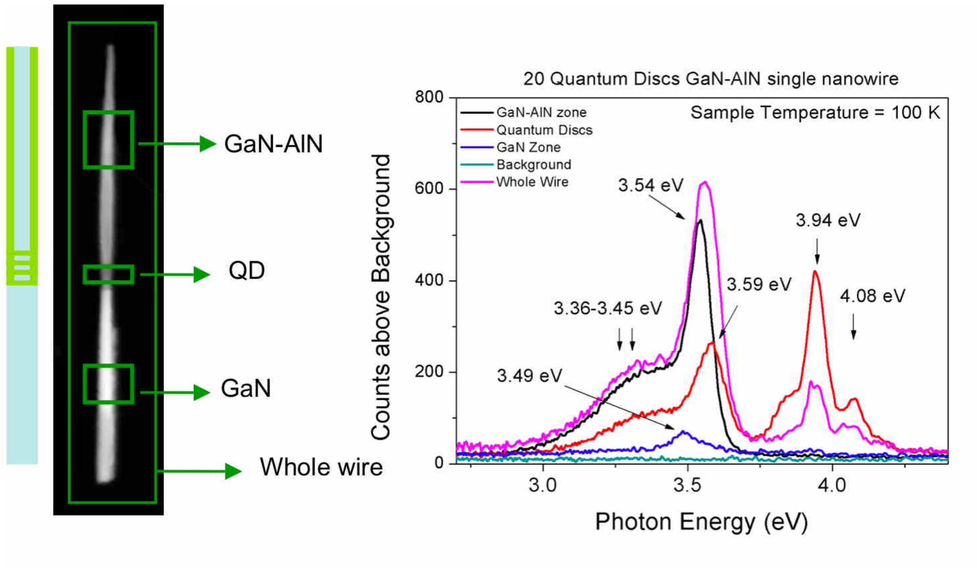

Figure 8: Measurement of the cathodoluminescence of single nanowires of a composite GaN/AlN nanowire with quantum discs (QD) at 100 K

Furthermore, several high-impact articles (**41** peer-reviewed papers including 1 **Nature Physics**, 2 **Nature Photonics**, 1 **Review of Modern Physics**, 4 **Phys. Rev. Lett.**, 1 **Advanced Materials**, 1 **JACS** and 6 **Nano Letters**.) have been published as a result of the activities of the consortium, and a impressive number of contributions in conferences (**119** including 6 **plenary talks**, 48 **invited talks** and 37 **contributed**) have arisen.