From classical optics to nanophotonics

Ludovic Escoubas, François Flory, Judikaël Le Rouzo, Gérard Berginc

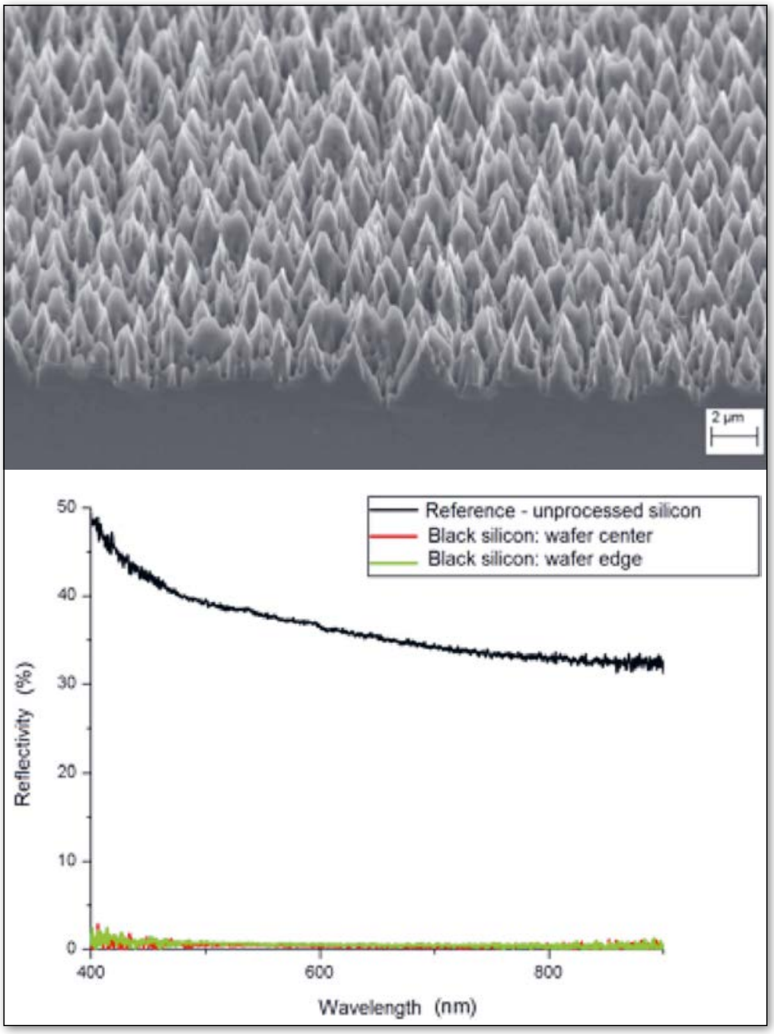
FROM CLASSICAL OPTICS TO NANOPHOTONICS

François Flory[1], Ludovic Escoubas[1], Judikaël Le Rouzo[1], Gérard Berginc[2] – DOI: https://doi.org/10.1051/epn/2018503

IM2NP – Faculté des Sciences et Techniques – Avenue Escadrille Normandie Niemen, Service 262 – 13397 Marseille cedex, France
THALES Optronique SA – 2 avenue Gay-Lussac – 78990 Elancourt, France

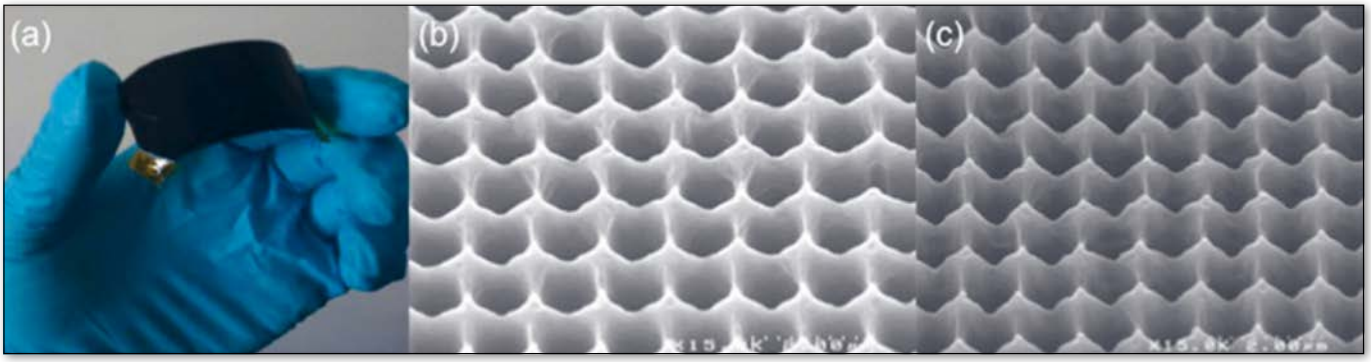
Nanophotonics is a very large and rich young field experienting a very rapid development worldwide. It is based on the study of light/matter interaction at low dimension. Several books are dedicated to different aspects of nanophotonics [1].

A long list of philosophers/scientists allowed understanding the nature of light and of its interaction with matter, the development of optical instruments and of lasers. We can briefly cited some of them who are known to bring important steps in these progresses. By trying to explain vision, Greek like Euclid (300 B.C.), Hero (60 A.D.), Ptolemy (120 A. D.) and then the Arab scientist Alhazen (1000 A.D.) described light propagation, till 13th century Italian glassworkers made lenses that were used for spectacles. Kepler (1604) decribed the propagation of light through lenses with geometrical optics, and he applied his studies to the eye. Lippershey invented the telescope soon before Galileo (1609) produced his own telescope and started to study planets and moons. Snell, Descartes(~1637), Newton (~1704) , Grimaldi (~1665), Huygens (~1690), Euler (1746), Gauss (~1800), Young (1803), Fraunhofer(1814), Fresnel (1819) , Abbe (1887)... allowed to deepen the understanding of classical optics by extending the notion of rays to the notion of waves. This has led to the development of new instruments and to define their resolution limit because of diffraction. Maxwell (1873) derived a set of four famous equations based on the electromagnetic nature of light waves to model light propagation. An important revolution started with Planck (1900) describing the blackbody radiation by assuming that it could only change as an integer number of small quanta. Einstein (1905) was able to explain the photoelectric effect based on these quanta of light named photons by Lewis (1926). In the sixties Gould, Townes, Schawlow, Maiman, Basov, Prokhorov were the pioneers of laser...



▾ **FIG 1:** (a) SEM image of Black Silicon surface obtained by cryogenic process. (b) Cryogenic plasma process black silicon reflectivity compared with unprocessed silicon. [10]

With the steady development of microelectronics and now of nanoelectronics, the question of developing very small optical components and systems arises. The main problem was first to cross the barrier of diffraction limit. Progresses in photolithography are obtained by using EUV (Exteme ultraviolet) and immersed optics to reduce the Critical Dimension, still dealing with difffraction. Quite early, in the middle of the twentieth century, materials with dimension smaller than the wavelength were already studied to make optical coatings which are used to control the spectral distribution of light and this is still a very active field of research with a wide range of applications [2]. 1D gratings were used to control the spatial distribution of



▲ FIG 2: (a) Photograph of the optical metafilter. (b) Top and (c) tilted views from SEM images of the tungsten inverted cone gratings.[11]

light. These components are based on interferences or diffraction. Most of optical thin films exhibit naturally a complex nanostructure, in particular a columnar structure when deposited by conventional thermal evaporation. This structure induces anisotropy . By acting on the deposition conditions thin films can be sculptured (STF) to control light polarization [3]. Surface roughness induces light scattering. In some extend, the spatial distribution of the scattered light can be shaped by controlling the roughness statistic [4]. we will see later that surface micro/nanostructures can be used to make broadband antireflection effect on silicon.

With technical progresses it now becomes possible to consider controlling both spectral and spatial properties of light by using materials with defined 2D or 3D structures. This very rich field of photonic crystals (PCs), still in development, finds already numerous applications such as chemical and biological sensors, solar light harnessing , broadband optical filters, controlled light emission, very small integrated optical circuits, low threshold lasers, interconnections... The optical density of state and the band dispersion can be engineered with PCs by using Bloch functions and band diagrams as in electronics [5]. It is then possible to control the permittivity and the permeability of matter by mixing several materials at small dimensions. Such metamaterials can exhibit effective refractive index not readily available in nature such as negative or nul effective index. They are used to slow light, to transform a gaussian beam in a plane wave, to make flat lenses, to perform high resolution imaging, cloaking, more generally to structure light. They can also be designed to engineer radiative decay or to exhibit functions inspired by quantum physics. Photonic Floquet topological insulators [6] can be obtained; optical vortices can be generated giving an orbital angular momentum to photons.

Another field of nanophotonics is based on the use of evanescent waves. As example, Scanning Near field Optical Microscope uses evanescent waves collected by a tapered optical fibre to make a high resolution image of a surface lightened in total reflection from below.

The optical properties of low dimensional materials get a better understanding since a few years. The permittivity and the permeability of materials depends on phenomena at such small scale. The susceptibility is coming from local oscillators. In classical physics, atoms and molecules in dielectrics can be seen as dipoles with resonant frequencies. Absorption bands are centered on these frequencies. Generally light interaction with matter takes place on a length in the order of the wavelength. It concerns a large number of atoms or molecules. The response of the matter is then an incoherent sum of the individual responses and the absorption band is broad (inhomogeneous broadening). In a mixture of matter at dimension smaller than the wavelength the effective permittivity can be obtained by the effective medium theory. When the matter is in smaller dimension, like in nanocrystals of dimension less than about 10nm, the local oscillators give a coherent response leading to much narrower absorption bands.

On the quantum physics point of view, the optical properties of matter depends on the discretise electron energy levels in the atoms and on phonon levels in molecules. The oscillators are the dipoles composed of the nuclear and a peripherial electron in case of atoms and of discrete vibrational/rotational modes in molecules. When a material limited in 1D, 2D or 3D is surrounded by a material in which electrons have a higher potential, the electron are confined and their wavefunction may exhibit resonances, like a particle-in-a-box or an electromagnetic wave in a microcavity. The electron energy levels are then discrete, as in an atom. It is necessary for this that the dimensions are limited to less than the thermal de Broglie wavelength of a few tenths of nanometers or less, depending on the wavelength and the semiconductor concerned. These materials are called quantum wells, quantum wires and quantum dots.

Not only the absorption spectra and the complex refractive indices are dependant on the size of the structures but also their emission spectra. Some quantum dots are now well known to exhibit a size dependant photoemission wavelengh with quantum yield which can be close to 100%.

Quantum wells are widely used to make microlasers useful for numerous applications, including telecommunications. Functionalized Quantum dots (QD) can be used as tags and have more and more importance in imagery for biology and health. QDs are also used to make single photon source. They can be embedded in thin films for down conversion of solar energy or for backlighting in colour enhanced flat TV (QDTV).

It is now well known that a surface wave called plasmon polariton can be excited with an evanescent optical wave at the surface separating a metal and a dielectric. For metallic nanoparticles (NPs) in the order of some ten nanometers a plasmonic resonance can be excited with a propagating optical wave having the matched wavelength. The optical field can then be strongly localized around the NPs. This is exploited in particular to make sensors, to perform enhanced Raman scattering , to have local heating, single particle detection [7] *etc.*

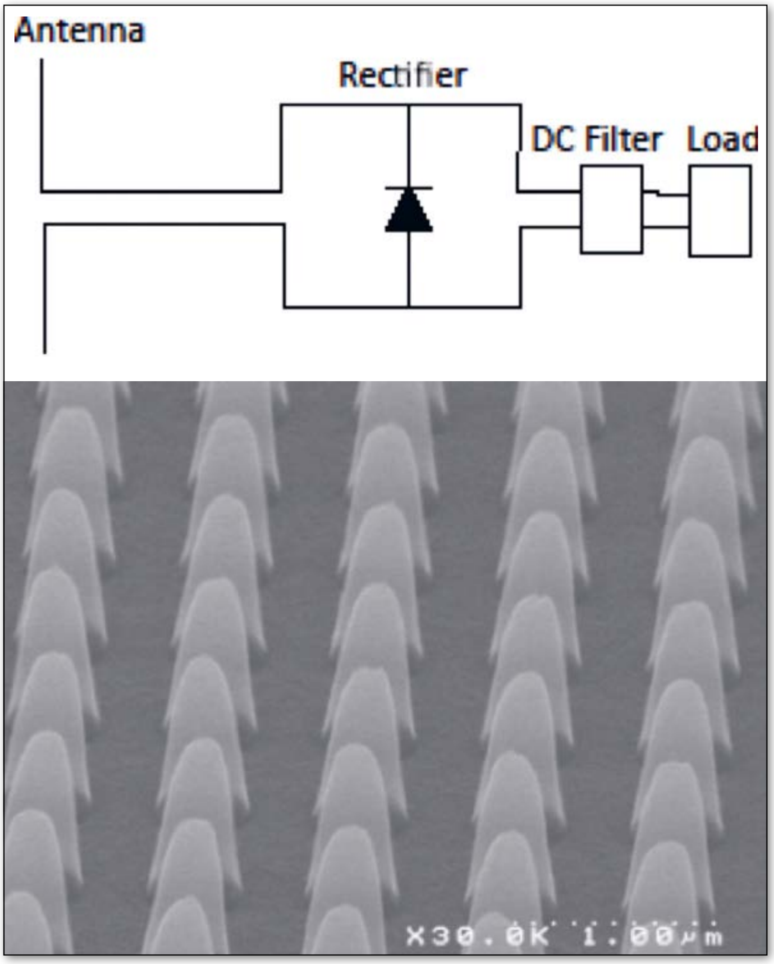
Metallic nanostructures can also be seen as optical antennas localizating the optical field. Coupled to a molecular diode they can be used to rectify the optical field (rectenna).

Some recent advances in nanophotonics applications are illustrated below.

Some examples of application of nanophotonics

Black Silicon

The silicon surface can be structured down to scales of some tens to some hundred of nanometers, on the order of the micron height, either on a periodic frame to get anti-reflective effects as efficient as those obtained with optical thin-films, either randomly to get what is called black Silicon (BS) [4,8,9]. The BS (see figures 1a: surface of BS and 1b: R versus λ) allows absorbing light very efficiently by trapping the photons in nanostructures. It is used in particular to realize photodetectors showing increased sensitivities in the Near InfraRed but also to improve the conversion efficiency of solar cells. The BS can be obtained by engraving the silicon surface using laser shooting through a sulphur vapour [8], by cryogenic etching, but also by room-temperature reactive ion etching (RIE) using appropriate process parameters [10].



▾ FIG 3: (a) Schematic of a rectenna. (b) SEM image of nanopyramids obtained by nano-imprint lithography. [16]

Metafilters

It is also possible to combine effects of 3D structuring of flexible materials with thin coatings in order to realized more complex optical filtering functions [11]. For example, the figure 2 below shows an optical metafilter realized by NanoImprint Lithography (NIL) of a PVDF (Polyvinylidene fluoride) film covered with a thin layer of tungsten. Absorption of visible light and near IR is almost complete with the nanostructuring and the tungsten absorption, so the reflectance is close to 0, while in the Infrared reflectance is maximum close to 100% and therefore the coating emissivity is close to 0. This flexible metafilter finds applications in the field of coatings for optical stealth but also for thermophotovoltaics.

Optical antennae

If we were able to associate an optical nanoantenne, highly resonant in some wavelength range for example using plasmonic effects or gap plasmons, with diodes to rectify an alternating current at very high frequency to get a continuous current, one can imagine going beyond the photovoltaic effect and get a direct conversion of incident photons into a flow of electrons under the form of a Direct Current (DC). In doing so, it is theoretically possible to convert 44% of the photons of a spectral domain into current [12] as compared to the maximum theoretical efficiency of 33.2% achieved in a traditional single junction PV cell. These components, combining an antenna and a diode, are called rectenna for "rectifying antenna" (see schematic on figure 3a). It is possible to use Metal - Insulator - Metal (MIM) diodes [13] or even molecular diodes which rectifying properties are obtained by the asymmetry of the molecule for example with ferrocenyl alkane thiol, which ferrocenyl group is placed either on one side or the other of the molecule [14-16]. Figure 3b presents nanopyramids periodically positioned in order to be a set of resonant antennae. The resonant wavelengths are imposed by the sizes of the nanopyramids and by their periodicity. The molecular diodes are directly self-assembled on the nanopyramid surface.

Conclusion

There are many other important aspects of nanophotonics concerning high resolution microscopy, microparticle manipulations, structured light generation, quantum optics, non linear optics...

Even though many applications with impressive impact on information and communication society emerged, nanophotonics is still in its enfancy. It requires to consider jointly electromagnetic theory, condensed matter physics and quantum physics. Nanophotonics is more and more intimately associated with nanoelectronics.

Thanks to the rapid advances in nano technologies one can expect in the near future the development of applications, today unimaginable, by using coupled QDs to make artificial molecules, coupled metallic NPs, structures at the molecular or atomic level *etc.* with exciting fundamental problems to be solved, going closer to the intimate nature of light, matter and particles. ■

About the Authors

François Flory is emeritus Professor at Ecole Centrale Marseille. He performs his research at the Institute Materials, Microelectronics and Nanophotonics of Provence. He is author of more than 200 papers, books, book chapters and conferences in the fields of optical thin films, Micro/nano structured materials and components for optoelectronics and Photovoltaics. He is assessor for different research agencies and reviewer for several international scientific journals. He is co-editor of the journal OPTIK.

Ludovic Escoubas was graduated from Centrale Marseille (a French "Grande Ecole" of Engineer), and received a PhD in Optics in 1997. He is now Professor at Aix-Marseille University (AMU), vice-director of "Institut Matériaux Microélectronique Nanosciences de Provence" (CNRS Laboratory). His current research interests are photovoltaics and photonics. He has authored more than 250 papers and communications and holds 11 patents.

Judikaël Le Rouzo is presently associate professor in Physics at Aix-Marseille University, France. He received his Ph.D. in Physics from the Ecole Polytechnique, France. His research done at the IM2NP CNRS laboratory, is mainly centered on the optoelectronic devices such as photodetectors or photovoltaic solar cells. He is specialized in optics and photonics. He is author of more than 45 publications in the last 5 years. He is expert for different research agencies and reviewer for several international scientific journals.

Gerard Berginc received his Dipl-Engineer Physicist degree from Ecole Centrale de Marseille and his doctorate in theoretical physics. Currently, he is Chief Scientist at Thales Optronique and president of OPTITEC, the French photonics and image cluster. His research activities include fundamental electromagnetic scattering phenomena in ordered and disordered media, coherent effects in random media, localization phenomena, and nanophotonics. He has authored more than 200 papers and communications and holds more than 80 patents. He is a fellow member of the Electromagnetics Academy.

References

[1] L. Novotny and B. Hecht, *Principles of Nano-Optics*, Cambridge University Press, Cambridge (2006). M. Ohtsu, K. Kobayashi, T. Kawazoe, T. Yatsui, M. Naruse, *Principles of Nanophotonics*, CRC Press, (2008). S. V. Gaponenko, *Introduction to Nano-photonics*, Cambridge University Press (2012). D. L. Andrews, *Photonics, Volume 2: Nanophotonic Structures and Materials*, Wiley (2015). P.Meyrueis, K; Sakoda, M. Van de Voorde, *Micro and nanophotonic tehcnologies*, Wiley-VCH (2017)

[2] A. Piegari, F. Flory, *Optical thin films and coatings-from material to applications*, 2nd Edition, Elsevier, (2018)

[3] A. Lakhtakia and R. Messier, "Optics of Chiral STFs," Chapter 9 in Sculptured Thin Films: Nanoengineered Morphology and Optics, A. Lakhtakia and R. Messier, Edts, SPIE Press, Bellingham, WA (2005)

[4] V. Brissonneau, F. Flory, L. Escoubas, G. Berginc, *J. Appl. Phys.* **112**, 114325 (2012).

[5] K. Sakoda, *Optical Properties of Photonic Crystals, Springer Series in Optical Sciences*, W.T. Rhodes, T. Asakura, and K.-H. Brenner, Eds., Vol. 80, 2nd ed., Springer Verlag, Berlin (2005).

[6] M. C. Rechtsman, J. M. Zeuner, Y. Plotnik, Y. Lumer, D. Podolsky, F. Dreisow, S. Nolte, M. Segev and A. Szameit, *Nature* **496**, 196 (2013)

[7] M. Caldarola and M. Orrit, *EPN* **49/2**, 14 (2018).

[8] R. Younkin, J. E. Carey, E. Mazur, J. a. Levinson et C. M. Friend, Journal of Applied Physics **93(5)**, 2626 (2003)

[9] Gerard Berginc, *Appl. Phys. A* **122**, 318 (2016).

[10] L. Escoubas, V. Brissonneau, G. Berginc, J.-J. Simon, *Method for randomly texturing a semiconductor substrate, Grant US9941445B2, Priority 2014-06-*04, *Filing 2015-06-*02, *Grant 2018-04-*10, Publication 2018-04-10

[11] J.-B. Brückner, V. Brissonneau, J. Le Rouzo, A. Ferchichi, C. Gourgon, C. Dubarry, G. Berginc, and L. Escoubas, *Appl. Phys. Lett.* **104**, 081114 (2014).

[12] Garret Moddel, Sachit Grover Editors, *Rectenna solar cells*, Springer New York Heidelberg Dordrecht London (2013)

[13] E. C. Anderson, T. L. Bougher, and B. A. Cola, *Adv. Electron. Mater.* 2018, 170 - DOI: 10.1002/aelm.201700446

[14] W. Du, T. Wang, H.-S. Chu, L. Wu, R. Liu, S. Sun, W. K. Phua, L. Wang, N. Tomczak and C. A. Nijhuis, *Nature Photonics* **10**, 274 (2016).

[15] D. Duche, U. Planchoke, F.-X. Dang, J. Le Rouzo, M. Bescond, J.-J. Simon,T. S. Balaban, and L. Escoubas, *Journal of Applied Physics* **121**, 115503 (2017).

[16] C. Reynaud, D. Duché, Carmen M. Ruiz, U. Palanchoke, F-X. Dang, L. Patrone, J. Le Rouzo, S. Labau, N. Frolet, C. Gourgon, A. Charaï, C. Alfonso, C. Lebouin, J-J. Simon and L. Escoubas, *Journal of Nanoparticle Research* **19(12)**, (2017)