



## Advanced Functional Materials 10<sup>th</sup> Anniversary Top Ten Papers

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Being invited to write a personal Perspective on one of our materials research papers, published in the top-rank journal *Advanced Functional Materials* and that has proven to have long lasting impact and inspirational to others in materials science and technology, is one of the greatest rewards in the life of a scientist and indeed a great complement.

It has been almost a decade since San Ming Yang, Hernan Miguez and I published our paper *Opal Circuits of Light – Planarized Microphotonic Chips* in *Advanced Functional Materials* 2002, 12, 425-431. This research was performed in the euphoric days of the optical telecommunication boom when 3D photonic crystals with an omni-directional photonic bandgap (PBG), were promising to transform the way in which one could guide, bend and localize light in sub-micron dimension optical circuits. The dream of the all-optical computer was beginning to look like reality.

A couple of years before, we had a major breakthrough with our publication in *Nature* 2000, 405, 437-440 that reported the first large scale synthesis of the silicon inverse opal, a bottom-up self-assembled photonic crystal with an omni-directional PBG. At the time, there was a lot of excitement in the materials research community that this kind of silicon-based PBG material would enable a wide range of predicted miniaturized optical devices. But to realize the goal of integrated microphotonic crystal circuits made of this kind of material it would be necessary to planarize opals on silicon wafers in much the same way as Jack Kilby had planarized microelectronic circuits in silicon wafers. Recall this was responsible for the development of today's integrated circuits that spawned the information communications technology revolution and for which he received the Nobel Prize in 2000.

This was our inspiration to try to reduce to practice the planarized microphotonic crystal chip and demonstrate the novel concept of opal circuits of light, the subject of our 2002 *Advanced Functional Materials* paper. The enabling leap to achieve this objective was to use soft-lithographically defined anisotropically-etched surface relief patterns in silicon of predetermined size and shape as templates to direct the evaporation induced self-assembly of microsphere opals therein. The structural and optical quality of micropatterned opals with various geometries made in this way was impressive and the ability to invert them in silicon using chemical vapour deposition with sacrificial etching of the opal template represented an important step on the road to on-chip silicon-based photonic crystal devices exemplified by optical waveguides, switches and lasers.

Significantly, this bottom-up opal single inversion technique and its extension to double inversion in a wide range of metals, semiconductors and dielectrics proved to be the founding strategy for similar processes applied to all kinds of polymeric photonic crystal templates made by top-down holographic interference lithography, direct laser writing and phase-mask methodologies. Single and double inversion strategies of the kind developed in our work could prove to be the enabling technology for making top-down photonic crystal devices and circuits.

This was the good news. The bad news was that the continued development of this opal templating work ran into two insurmountable hurdles. The first was related to the difficulty of eliminating adventitious defects like microsphere vacancies, stacking faults, dislocations, microcracks and so forth, in the photonic crystal lattices, which caused deleterious multiple light scattering and light losses that was unacceptable to optical engineers trying to make real devices. The second was the demise of the optical telecommunication industry (recall I this sector Ottawa was Silicon Valley North) through oversupply making it hard to justify continuation of the work and difficult to attract funding to pay the costs of research. So the motivation for continuing to expand and enrich our work on opal chips was waning and my group, as well as many others around the globe working on this class of self-assembled photonic crystals, began to ask the question, opals: what is next?

And indeed it came to pass that there was no shortage of new and exciting avenues to be explored as witnessed by the torrent of incredibly creative work on colloiddally assembled photonic crystals with both spherical and non-spherical building blocks that followed and which exploited their widely tuneable structure, composition, refractive index contrast, porosity, surface functionality and morphology, the latter being fashioned in the form of opal fibres, opal spheres, opal films and opal surface patterns.

This high level of synthetic control led to the development of novel kinds of photonic crystal chemical and biochemical sensors, chromatography stationary phases, lithium ion battery electrodes, dye sensitized and silicon solar cells, organic photooxidation catalysts, mechanically tuned biometric security and banknote anti-counterfeit devices, electrically and magnetically tuned full color reflective displays, light emitting diodes and band-edge lasers, to name but a few of the emerging directions for opal-based materials research.

It is worth noting the far reaching impact of the paradigm of spatially-directed self-assembly of microspheres into periodic arrays, described for the first time in our Advanced Functional Materials paper, in other areas of nanoscience. High profile offshoots are those involving the self-organization of block copolymers, nanocrystals, nanorods and nanotetrapods in predefined surface relief patterns to form a treasure-trove of amazing new nanostructures. These often display hierarchical architectures and fascinating properties that evoke functionality of a novel and unforeseen kind, inspiring development of a wealth of innovative applications.

On a more personal note, my groups work on opal-based tuneable structural color led to the founding of an Ontario company Opalux Incorporated ([www.Opalux.com](http://www.Opalux.com)) whose mission is to scale, manufacture and commercialize photonic crystal technology that enables power-saving full-colour reflective displays, food packaging that changes colours when the contents go bad, photocatalysts that clean up environmental pollution, and privacy protecting printable serial numbers and security codes that can become invisible to the human eye when necessary.

Hopefully one can appreciate from this brief personal Perspective that in the world of materials chemistry there is no such thing as a bad material. While basic research on opal-chips never transitioned into an optical communications technology because of intrinsic defects that were difficult to eliminate as well as an optical telecom industry downturn the recovery of which took years, it did inspire a cornucopia of other kinds of defect-tolerant opal-based materials research around the world, some of which will end up in a range of exciting and colourful new products, like those being developed by Opalux.