Technology breakthroughs win 2009 Physics Nobel

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The 2009 Physics Nobel Prize, awarded to Charles Kao for his pioneering research on glass fibres for optical communication and to Willard Boyle and George Smith for their invention of the charge-coupled device (CCD) only re-emphasizes the all-pervading importance of fibre-optics and semiconductor technology in every aspect of modern life. It also reminds us that India missed the semiconductor revolution. Kao and Hockham's paper was written in 1966 when they were at the Standard Telephone Laboratories in UK. The key element was their proposal for long distance communication using glass fibres. Boyle and Smith invented the CCD for memory, signal processing and imaging applications a few years later while working at the Bell Telephone Laboratories (BTL) in the USA.

It is worth remembering that the first book on the subject entitled *Fibre Optics: Principles and Applications* was written in 1967 by Narinder Singh Kapany, who after studying and working in India in a defence laboratory, did his Ph D at Imperial College, London in 1955 (ref. 1). His guide was the noted optical physicist Harold Hopkins. Together they worked on optical fibres for medical imaging. In a *Scientific American* article written in 1960, Kapany coined the term fibre-optics and as such is regarded as the 'Father of fibre-optics'. Between 1955 and 1965, he published 55 papers being the lead author in 45 of these. In 1960, long before Kao, he founded Optics Technology Inc. and was Chairman of the Board, President and Director of Research for 12 years. Thus there is strong general opinion that he should have shared the prize with Kao. Nobel Prize 'rules' however permit only three recipients for a prize and thus Art Gossard was deprived of a share of the prize for the discovery of the Fractional Quantum Hall effect in 1998.

The prizes this year were awarded for work done 40 years ago while in other cases, such as the discovery of the oxide superconductors or the invention of the scanning tunnelling microscope, the awards came within a few years of their announcement. There has also been much debate as to whether any fundamentally new physics was involved in the invention of the CCD and whether this was no more than a technological achievement. Compare this with the invention of the bubble chamber by Donald Glaser and the spark detector by Georges Charpak, both awarded Nobel Prizes in 1960 and 1992 respectively, about which much the same can be said. What is more, these earlier inventions impacted only the field of nuclear and particle physics whereas fibre optics has certainly 'revolutionized' the entire field of communication and CCDs brought photonics to the door of the common man.

Since the Second World War, the use of microwaves led to rapid spread of overland communication. However microwaves, travelling in straight lines, required repeaters every 100 km to overcome the earth's curvature. Many attempts were made to use hollow flexible waveguides for long distance microwave propagation but these proved cumbersome and expensive. The launch of earth satellites in the late fifties and sixties provided an attractive alternative. Signals could be bounced off satellites for broadcast, remote sensing and information transfer. It was shown by Arthur Clark, author of '*2001 – A Space Odyssey*' that three synchronous satellites in stationary orbits around the earth could cover the entire earth's surface.

In 1966, Kao and Hockham in the UK proposed the use of thin glass fibres for long distance optical communication. Although made of glass, these fibres were flexible and as strong as steel and could trap light waves due to their higher refractive index, causing total internal reflection. In fact Colladon in France in 1841 (ref. 1) (not Tyndall as often attributed) showed that a stream of water could act as a light guide, as demonstrated in the Paris Exhibition of 1889. However the available glass fibres were strong absorbers, which attenuated light within a few metres. It took the combined efforts of several major laboratories in USA, UK and Japan to reduce this loss from 1000 to 0.2 dB/km by 1970. The key to this advance was the removal of all impurities from the glass fibre, which thus consisted of pure silica (SiO_2). Another crucial factor was the presence of a cladding with slightly lower refractive index for light confinement within the core. Light could thus travel 100 km through the fibres without the need for amplification. These fibres had diameters of 10–100 microns, ideal for the use of a semiconductor laser as source and a *p–i–n* photodiode as detector. Small diameter fibres supported only a single mode as

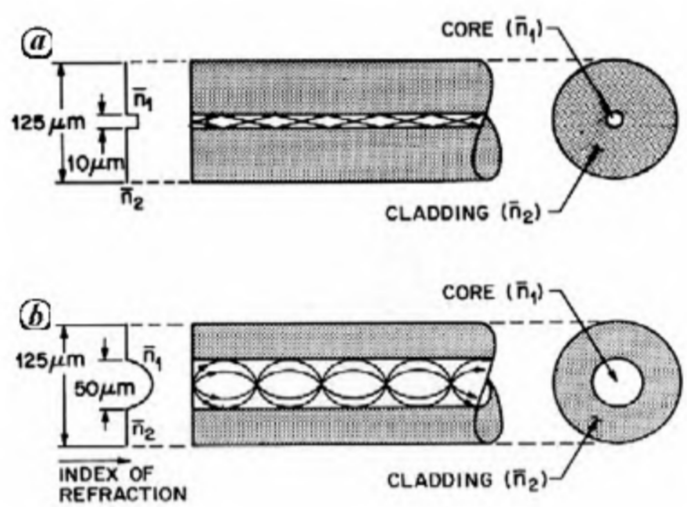

Figure 1. Types of optical fibres: ***a***, Single mode; ***b***, Multi-mode.

shown in Figure 1 while larger diameter could transmit many modes with larger dispersion.

In 1962 as a spin-off from the semiconductor industry, the semiconductor laser was invented by three groups in USA. These were tiny devices compared with gas or solid-state lasers with inferior properties, requiring operation at low temperatures. Alferov in the USSR was successful in making heterostructure lasers which could operate at room temperature for which he was awarded a Nobel Prize in 2000. Lasers were said to be inventions looking for applications since unfortunately free space propagation of light waves from lasers was subject to atmospheric disturbances.

The invention of the glass fibre was a godsend for the development of the semiconductor laser. The marriage of semiconductor opto-electronics and fibre glass technology resulted in what is now known as fibre-optic (FO) communication systems. Its advantages are wide bandwidth, flexibility, low cost compared to copper cables and freedom from interference. The first generation of FO systems worked at 0.9 microns wavelength because of the available GaAs/AlGaAs lasers, but it was soon realized that the attenuation of pure silica fibres was lowest at 1.55 microns where dispersion was also zero. Thus the second generation of FO systems moved to 1.3 microns and the third generation to the desired 1.55 microns[2]. In each case, the semiconductor sources (light emitting diodes, LEDs) or lasers and the corresponding detectors had to be tailor-made for these wavelengths. Optical fibres are now manufactured at rates of millions of km per year and span all the major oceans through a wide undersea network. Fibres have been made into amplifiers and lasers using doping with erbium, resulting in what is known as erbium-doped fibre amplifiers (EDFA). These permit direct light amplification at repeaters, without recourse to opto-electronic detectors and amplifiers[3]. The transmitted light is in digital form and with time-division multiplexing (TDM), a number of signals can be sent simultaneously. Now the refractive indices of fibres can be controlled by doping (almost like the doping profiles in semiconductors) to make dispersion-compensated fibres over a range of wavelengths. Thus frequency-division multiplexing (FDM) can be used to transmit hundreds of signals through the same fibre.

The invention of the CCD was a different story. Although the transistor was invented at BTL in the late forties, BTL fell behind when it came to the invention of the metal oxide semiconductor (MOS) transistor in 1960 and the integrated circuit (IC chip) by Kilby and Noyce, both of which occurred in Silicon Valley. Kilby incidentally was awarded the Nobel Prize for Physics in 2000 for developing the silicon chip. A group of researchers at Bell Labs in the mid-sixties came up with the idea of a magnetic bubble memory device which threatened the supremacy of semiconductor technology.

It was with this background that Boyle and Smith hit upon the idea of a semiconductor memory, where information was stored as electronic charge in potential wells, rather than through current or voltage. A closely spaced array of MOS devices was conceived with direct charge transfer between their potential wells[3,4]. In the memory device, the signal is introduced into the first element by injection through a forward-biased p–n junction and the output detected by a reverse-biased diode. However, for imaging applications which have now become dominant, electrons and holes are created by incident light, their density being proportional to the light intensity. Minority carrier electrons in a p-type semiconductor are confined in a potential well under the first element, called a pixel. The depth of the potential well is controlled by the gate voltage as in a MOS diode. Separate elements are placed very close together such that by applying a sequence of voltages to the gate electrodes, charges generated by light can be shifted from one pixel to the next. This is illustrated in the diagram of a three-phase CCD where pulses are applied to gate electrodes with a phase difference of $360°/3 = 120°$. A sequence of pulses permits horizontal transfer across a large number of pixels, e.g. 256 and the charge collected sequentially at the output electrode. The elements being connected by both horizontal and vertical grid lines, it is possible to collect the charge on each element (pixel) by scanning sequentially and thus obtain the picture (light intensity distribution) of an array of say 256×256 pixels. Thus the timing of the clock pulses is of utmost importance.

The virtuosity of the CCD lay primarily in the fabrication ensuring that the efficiency of charge transfer between pixels was as high as 99.9999% for good imaging, since otherwise the electrons would be lost after multiple transfers. If the transfer inefficiency is ε and the number of transfers is N, then the condition for satisfactory charge transfer without degradation is $N\varepsilon < 0.01$. For example if $\varepsilon = 10^{-6}$, $N = 10^4$ satisfies the given condition. The other important parameter is the speed of transfer required for faithful imaging. The electron transfer mechanism has three components due to thermal diffusion, self-induced drift and fringing field effect. With very close spacing between the wells, which was quite an achievement in the sixties, a maximum frequency of operation up to 10 MHz was achieved with Si CCDs. For

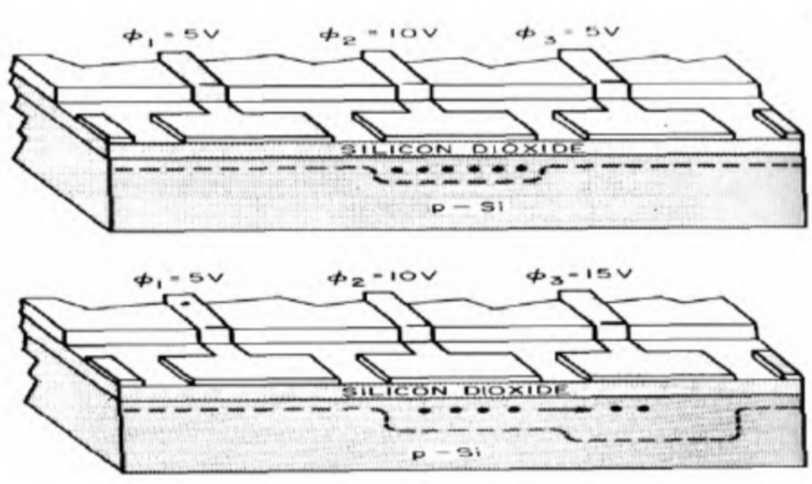

Figure 2. Three-phase CCD showing electron transfer from second to third well as the gate voltages increase from 5 to 10 V and 15 V (ref. 4).

GaAs CCDs, 500 MHz and higher has been achieved.

The CCD was highly sensitive and could detect and store less than 100 electrons in a well. Bell Labs having invented the Picturephone wanted to incorporate CCDs in these devices, but for a variety of reasons (including human psychology!) the Picturephone never caught on. It was the Japanese who realized the great potential of CCDs about 10 years later and converted it into a highly successful commercial product.

The first and most common CCDs are made from silicon having silicon oxide as a gate insulator and polysilicon as gate. CCDs are of two types – surface (SCCD) and buried channel (BCCD) operating on the same general principle. The latter has the advantage of avoiding surface traps but has lower speed. First used in TV cameras instead of bulky Vidicon tubes, their mass production has led to widespread use in digital cameras and a variety of optoelectronic devices. CCDs have also been made from other semiconductors such as indium antimonide and mercury cadmium telluride for missile detection and night vision applications. Hence, these have great strategic importance.

As usual, India was a late and hesitant entrant in both these fields. CCDs were demonstrated at Indian Institute of Technology (IIT), Delhi, a decade after their invention and are now being fabricated in some laboratories as infrared detectors. Important theoretical studies on fibre-optic propagation have been carried out at IIT Delhi. A couple of public sector industries that ventured into manufacture of optical fibres failed to meet the competition after liberalization and are now engaged mainly in packaging. Optical fibres for special applications are now being fabricated at Central Glass and Ceramic Research Institute (CGCRI), Kolkata.

These awards should help dispel the common belief that discoveries in science are the drivers of technology. In actual practice, it is often the other way around – the invention of the CCD proved to be a boon to space science and astrophysics and led to startling discoveries from the Hubble Telescope. Photography was discovered by enterprising scientists back in the 1830s examining the peculiar properties of silver halides but a plausible theory did not emerge untill 100 years later. Would the discovery of X-rays been possible without photography? Much closer to present times, xerography was invented by an American who had only vague ideas as to the science behind the process – the physics began to be understood 30 years later! Thus there is a complex symbiotic relation between science and technology rather than the conventional wisdom trotted out in textbooks.

1. Hecht, J., *City of Light*, Oxford, 1999.
2. Ghatak, A. K., *Optics*, Tata-McGraw Hill, 1993, 2nd edn.
3. Jha, S. S. (ed.), *Perspectives in Optoelectronics*, World Scientific, Singapore, 1995.
4. Sze, S. M., *Physics of Semiconductor Devices*, Wiley, New York, 1991.

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MEETINGS/SYMPOSIA/SEMINARS

National Conference on Impact of Climate Change on Biodiversity of Insects and Environment (CBI' 10)

Date: 15–16 March 2010
Place: Coimbatore

Themes include: Impact of climate change on the biodiversity, bioinformatics and insect migration; Impact of climate change on the crop pests and food production; Impact of climate change on the forestry insects diversity and ecosystem; Impact of climate change on the insect vector and disease surveillance/outbreak.

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National Symposium on Conservation Horticulture

Date: 21–23 March 2010
Place: Dehradun

Thematic areas: Conservation and management of bio-diversity for future uses; Conservation through efficient management of natural resources; Tissue culture and genetic improvement through biotechnology; Development of cultivars/varieties for changing climate; Health management of seed and planting material; Protected cultivation; Plant architecture, engineering and management; Timely diagnosis and plant health management in production system; Post harvest management of horticultural produce and value addition; Marketing, trade, industry, intellectual property right; Policy issues for conservation horticulture; Extension, transfer of technology, farmers issues; Education and career opportunities in horticulture; Open session.

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