Scientific Background on the Nobel Prize in Physics 2009

TWO REVOLUTIONARY OPTICAL TECHNOLOGIES

compiled by the Class for Physics of the Royal Swedish Academy of Sciences

Two revolutionary optical technologies

During recent years, information technology has revolutionized our daily life. This is to a large part due to the development of electronic and optical devices and systems. The Nobel Prize in Physics 2009 honors three scientists, who have played important roles in shaping the modern information technology, with one half to **Charles K. Kao** and with **Willard S. Boyle** and **George E. Smith** sharing the other half.

Charles K. Kao initiated the search for and the development of the low-loss optical fiber presently used in optical fiber communication systems. Willard S. Boyle and George E. Smith invented the charge-coupled device (CCD) presently used in many digital cameras and in advanced medical and scientific instrumentation.

Optical fiber with high transmission

The guiding of light in media using the concept of total internal reflection was first discussed during the 19th century. In 1841, D. Colladon at the University of Geneva demonstrated light guiding in a water jet, while at about the same time, J. Babinet in France made similar observations and even extended the idea to guiding in bent glass rods. The idea is often attributed to J. Tyndall who demonstrated the guiding of light in a

Fig. 1: Optical fiber. The refractive index of the core is slightly higher than that of the cladding. Typical dimensions are 10 or 50 micrometers for the core and 125 micrometers for the fiber. In addition, a protecting plastic "buffer" is placed around the fiber.

water jet at the Royal Society in London in 1854, following a suggestion by M. Faraday. One can argue however, that the phenomenon was known since ancient times, with small (colored) glass pieces used as decoration in Egypt or Mesopotamia. Light guiding in large water jets was even used for entertainment purposes, with illuminated fountains shown at the 1889 Universal Exposition in Paris (see [1] for a historical review).

The first ideas of applications of light guiding in glass fibers (i.e. small glass rods) date from the late 1920's. They were all about image transmission through a bundle of fibers. The motivation was medicine (gastroscope), defense (flexible periscope, image scrambler) and even early television. Bare glass fibers were, however, quite leaky and did not transmit much light. Each time the fibers were touching each other, or when the surface of the fibers was scratched, light was led away from the fibers. A breakthrough happened in the beginning of the 1950's with the idea and demonstration that cladding the fibers (see Figure 1) would help light transmission, by facilitating total internal reflection. At about the same period, H.H. Hopkins and N.S. Kapany at Imperial College in London successfully constructed a bundle of several thousand fibers 75 cm long and demonstrated good image transmission properties [Nature <u>173</u>, 39 (1954)]. Combining the fiber bundle technology with cladding, some applications, in particular the gastroscope,

went all the way to industrial production. The theory of light propagation into fibers was described by N.S. Kapany, and improved later by E. Snitzer [J. Opt. Soc. Am. 51, 491 (1961)]

The optical region of the electromagnetic spectrum, corresponding to wavelengths in the visible, near infrared or ultraviolet spectrum, has long been considered attractive for communications. The frequency of the light allows for high signal modulation frequency and consequently to high transmission speed. In 1880, G. A. Bell patented an air-based optical telephone called "Photophone", consisting in focusing sun light on the surface of a flat mirror vibrating with sound. The light was then sent to a detector of selenium coupled to a telephone receiver. A few later ideas were also patented, one of them in Japan even suggesting quartz as a transmission medium. In the 1950's, however, very few communication scientists considered optical communication as a viable concept.

100 years ago, G. Marconi and K.F. Braun were awarded the Nobel prize "in recognition of their contributions to the development of wireless telegraphy". 50 years ago, electronic and radio communications were in rapid expansion. The first transatlantic cable was installed in 1956 and satellites would soon allow even better coverage. The first communication satellite was launched in 1958. Research in telecommunication concentrated mainly in shorter radio waves, in the millimeter range, with the aim to reach higher transmission speeds. These waves could not travel as easily in air as longer waves, and the research focused on designing practical waveguides.

The invention of the laser in the early 1960s (Nobel Prize in 1964 to C.H. Townes, N.G. Basov and A.M. Prokhorov) gave a new boost to the research in optical communication. Shortly after the pulsed laser demonstrated in ruby by T.H. Maiman, A. Javan built the first continuous-wave laser using a mixture of He and Ne gas. Semi-conductor lasers appeared almost at the same time, but were at first not so practical, since they required high currents and could not work at room temperature. A few years later, the introduction of heterostructures (Nobel Prize in 2000 to Z.I. Alferov and H. Kroemer) enabled operation at room temperature, making them ideal light sources for optical communication.

An intense search for suitable transmission media in the optical domain began at the beginning of the 1960s. The optical fiber was, however, mostly set aside because of its high attenuation. Attenuation can be expressed by a coefficient (in dB/m)

$$\alpha = \frac{10}{L} \log_{10} \frac{P(0)}{P(L)},$$

where $P(0)$ and $P(L)$ are the input and output power respectively, and L is the fiber length. The attenuation of the first optical fibers was typically 1000 dB/km, implying that only 1 % of light got transmitted in twenty meters of fiber. Other options, such as guiding of light through sequences of lenses or even gas tubes with temperature gradients to focus light were proposed and sometimes tested, but without much success. Various waveguides in the optical region were investigated. Both A.E. Karbowiak at STL (The Standard Telecommunication Laboratories), Harlow, UK and J.C. Simon and E. Spitz at CSF (Compagnie générale de télégraphie Sans Fil) in France realized that propagation of single modes into

Fig. 2: Different types of fibers, step-index multi-mode, single mode and gradient index multimode. The propagation of a few rays is also indicated in red, as well as the distribution of the refractive index to the right.

waveguides (for example, thin films) should be beneficial to optical communication, reducing dispersion and propagation losses. At Tohuku University, Japan (J.-I. Nishizawa, I. Sasaki) as well as at Bell laboratories, USA (S.A. Miller), optical fibers with a varying refractive index were proposed. In a gradient-index fiber, dispersion effects arising because spatial modes propagate at different velocities in the fiber are reduced compared to the step-index multimode fiber (see Fig. 2). These fibers were going to be exploited later, being the first-generation optical fibers to be used at 870 nm. However, none of the solutions could find any satisfactory remedy to the attenuation problem.
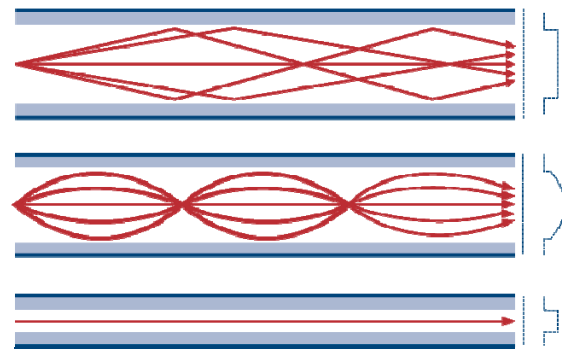
Charles K. Kao was a young engineer at STL working on optical communication. He started under the direction of Karbowiak, and then became in charge of a small group, which at first had only one coworker, G.A. Hockham. Kao was born in 1933 in Shanghai, China, and educated in Hong-Kong. He graduated in Electrical Engineering in 1957 at University of London and got a PhD at the University of London in 1965. Hockham was a young theoretician, whose work on the analysis of the effect of waveguide imperfections would lead to a thesis defended in 1969. They investigated in detail the fundamental properties of optical fibers with respect to optical communication. In particular, they did not consider the physics of waveguides only, as most of their research
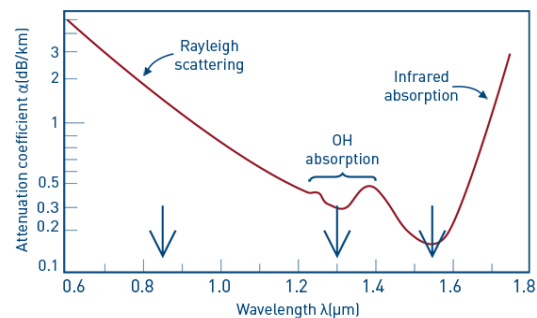

Fig. 3: Attenuation coefficient of silica as a function of wavelength. On the short wavelength side, attenuation is due to Rayleigh scattering, which varies as λ^{-4}, while on the long wavelength side, to absorption in molecules. Impurities due to OH radicals are usually difficult to remove. The favored wavelengths for optical communication are 1.3 and 1.55 μm.

colleagues did, but also the material properties. Their conclusions were presented by Kao in London in the beginning of 1966 and published in June [2]. The most important result was that losses in dielectric media were mostly caused by absorption and scattering (see Fig. 3). The predicted attenuation of a few dB/km was found to be much less than that measured at the time. Consequently, the latter was predominantly caused by impurities, in particular iron ions. Fibers with glass of higher purity could be a good candidate for optical communication. Damping caused by bending and waveguide imperfections, as well as propagation and radiation losses were also analyzed and found to be small. Single mode fibers were presented as the best transmission medium

Fig. 4: Spatial electromagnetic modes in a multimode fiber, from [2]. The top left one is the hybrid HE_{11} mode, the only one propagating in a single mode fiber.

for optical communication. Multimode operation would result in higher losses and temporal broadening due to higher dispersion. Single mode fibers could be made by choosing materials with close refractive indices. Spatial modes, indicating how light waves propagate in a fiber, were studied experimentally (Fig. 4) and a fiber attenuation threshold for viable optical communication based upon available laser power and detector sensitivity was set to 20 dB/km and predicted to be within reach. Kao concluded by a visionary statement [2]: "[...] a fibre of glassy material constructed in a cladded structure [...] represents a possible practical optical waveguide with important potential as a new form of communication medium [...] Compared with existing coaxial-cable and radio systems, this form of waveguide has a larger information capacity and possible advantages in basic material cost." At CSF in France, a young engineer A. Werts published a paper with similar conclusions in September 1966 [L'Onde Electrique, 46, 967 (1966)]. When discussing damping, he acknowledged Kao's work.

Kao, together with new coworkers, T.W. Davies, M.W. Jones, and C.R. Wright, continued this work with a series of careful measurements of the attenuation of light in glass and other materials at different wavelengths [J. Scien. Instr. 1, 1063 (1968); 2, 331 (1969); 2, 579 (1969)]. In particular, he showed that fused silica (SiO_2) had the purity required for optical communication. An intense worldwide search with the aim to produce glass fibers with low losses began, stimulated by Kao who was not only an inspired physicist but also a good communicator of his vision.

The problem to solve was to manufacture glass fibers without impurities. Kao had pointed to the right material, namely fused silica. Unfortunately, this material has a high melting temperature. At the time, its fabrication and manipulation was not easy and most laboratories first tried to draw fibers using other types of glass, without much success. Four years after Kao and Hockham's article, a research team from the Corning Glass Works in the United States, with
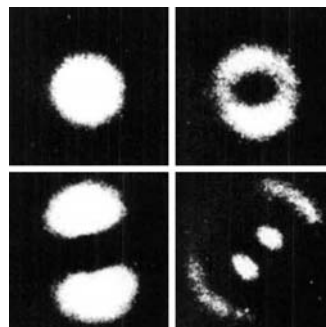
F.P. Kapron, D.B. Keck, P.C. Schultz, F. Zimar, under the leadership of R.D. Maurer, succeeded by a clever chemical method called CVD (Chemical Vapor Deposition) in making glass fibers of fused silica with the low losses that Kao had envisioned. To make a core and a cladding with very close refractive indices, they doped titanium in the fused silica core, and used pure fused silica in the cladding [Appl. Phys. Lett. 17, 423 (1970)]. A few years later, they even reached 4 dB/km at 850 nm, using germanium instead of titanium. Several other technologies were developed in Japan, USA and UK. J.B. MacChesney and co-workers at Bell Laboratories developed a modified CVD technique, allowing efficient production of optical fibers. Within a few years, attenuation less than 1 dB/km was achieved, even far below the threshold set by Kao. Today, attenuation of light at 1.55 μm wavelength in fibers is below 0.2 dB/km (see Fig. 3). A modern optical fiber is an extraordinarily transparent medium, with more than 95% light left after 1 km propagation.

Optical communication of today has reached its present status thanks to a number of break-throughs. Light emitting diodes (LEDs) and especially diode lasers, first based on GaAs (800-900 nm) and later on InGaAsP (1-1.7 μm), have been essential. The optical communication window has evolved from 870 nm to 1.3 μm and, finally, to 1.55 μm where fiber losses are lowest (see Fig. 3). Gradient-index fibers were used in the first optical communication lines. However, when moving towards longer wavelengths and longer communication distances, single-mode fibers have become more advantageous. Nowadays, long-distance optical communication uses single mode fibers almost exclusively, following Kao's vision. The first such systems used frequent electronic repeaters to compensate for the remaining losses. Most of these repeaters have now been replaced by optical amplifiers, in particular erbium-doped fiber amplifiers. Optical communication uses wavelength division multiplexing with different wavelengths to carry different signals in the same fiber, thus multiplying the transmission rate. The first non-experimental optical fiber links were installed in 1975 in UK, and soon after in the US and in Japan. The first transatlantic fiber-optic cable was installed in 1988.
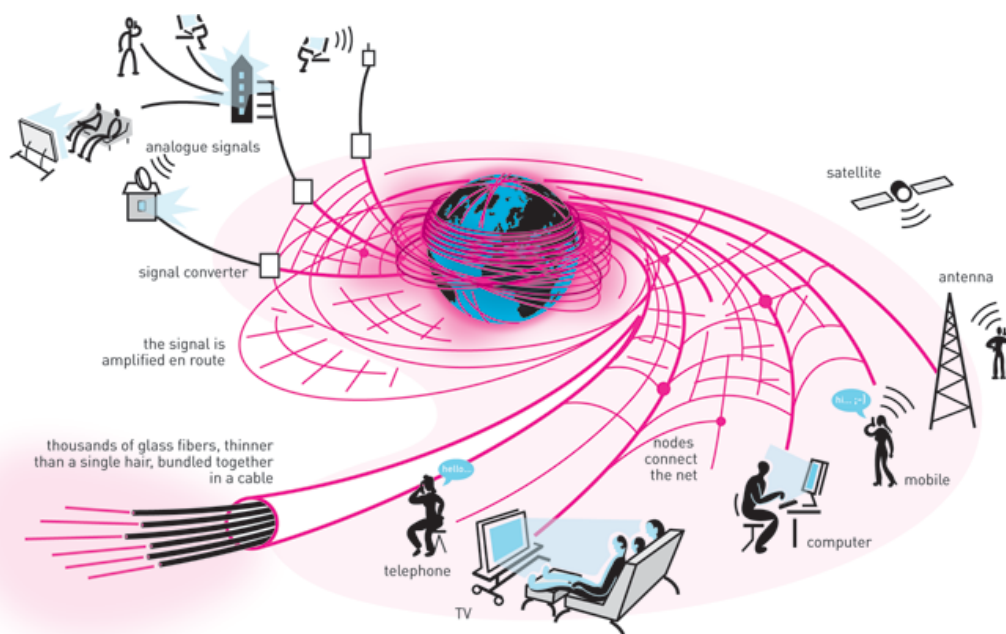

Figure 5: Artistic view of global communication

Global communication, and in particular internet and long-distance telephony, is now based primarily on optical fiber technology (see Fig. 5). As pointed out above, the main advantage of optical waves compared to radio waves is the high frequencies that allow high data transmission rate. Nowadays, several terabits per second can be transmitted in a single fiber which represents an increase by a factor of one million to what could be achieved fifty years ago with radio signal transmission. The number of optical fiber cables being installed all over the world is increasing rapidly. Fiber optics has also been important for a huge number of other applications, in medicine, laser technology and sensors. An interesting example of the use of fiber-optic communication in science is the advanced fiber optics network developed at the Large Hadron Collider at CERN in Geneva that will transfer large amounts of information obtained by the particle detectors to computer centers all over the world.

Useful references

1. J. Hecht, "City of light. The story of fiber optics", Oxford University Press (1999).
2. K.C. Kao and G.A. Hockham, "Dielectric-Fibre Surface Waveguides for optical frequencies" Proc. IEE, 113, 1151 (1966).

Charge-coupled Devices

The history of cameras and photography is very long with a number of important discoveries and developments. Old cultures, like those in China, Egypt and Greece, knew about the camera obscura phenomenon, where a hole in one wall produces an inverted image on the opposite wall in a dark room. This was used in primitive box cameras also employing lenses to produce better images, but without a recording medium. The history of the stored image, of photography, contains many names, a few of which will be mentioned below. Apparently the first still remaining photograph was produced by J.N. Niépce in 1826 using a camera obscura with an 8 hour exposure time. A negative image was produced in a layer of bitumen, a petroleum product, which hardens in light. An elaborate process was used to form a positive image from this negative. L.J.M. Daguerre developed a process to directly create a positive image on a silver covered copper plate exposed to silver iodide creating a light sensitive layer on the plate. The layer was treated with mercury vapor after exposure to obtain a positive image (called daguerreotype and released in 1839). W.H.F. Talbot invented in 1841, thus initiating modern photography, light sensitive papers containing silver salts for first obtaining a negative image and thereafter, through contact copying with another light sensitive paper, a positive image. He described also the steps necessary to develop the latent images formed in the papers. Several developments followed regarding the substrate used for the light sensitive layers. The idea to use emulsions (silver salts in gelatin) to create negatives was conceived around 1870 and the replacement of glass plates with a celluloid film around 1880. The roll of film was invented 1887 by a priest, H. Goodwin, and explored by G. Eastman. In 1888 the Eastman Kodak box camera for roll film appeared on the market.

Different schemes for color photography were also explored during the 19th century. G. Lippman was awarded the 1908 Nobel Prize in Physics for his color photographic process based on interference effects. One of the early important contributions to color photography was made by the pianist L.D. du Hauron, who 1869 suggested the so called subtractive method based on the fact that a pigment absorbs all colors but its own, which is reflected. Together with the light sensitive emulsions, this could be used for color photography. Traditional color films consist of three light sensitive emulsions with different sensitivities for light: top layer for blue, middle layer for green, and bottom layer for red. After a special development sequence a subtractive color image in yellow, magenta and cyan (a negative) is obtained for further processing. This is for example the principle behind Kodachrome film released 1935, which was invented by two musicians, L. Godowsky and L. Mannes.

Manufacturing of this film was only recently stopped as photographers have turned to newer films or, to a large extent, to digital imaging technologies. Kodak actually developed the Bayer filter mosaic pattern used for charge-coupled device (CCD) image sensors as early as 1975, only a few years after the release by Fairchild Semiconductors of the first large image forming CCD chip with 100 rows and 100 columns, and five years after the groundbreaking CCD invention

paper by W.S. Boyle and G.E. Smith. Another consequence of the development of digital imaging technology is the cessation of the production by Polaroid of instant picture products, 2008-2009.

Willard S. Boyle and **George E. Smith** were both at Bell Laboratories, New Jersey when they conceived the CCD device. Smith was working as a Department Head under Boyle, who was the Director of the Device Development Laboratory. Boyle was born in Amherst, Nova Scotia in 1924. He was educated at McGill University and obtained Ph.D. in Physics in 1950. He joined Bell Laboratories in 1953. Smith was born in White Plains, New York in 1930. He received a Ph.D. in Physics from the University of Chicago, in 1959. He joined Bell Laboratories in 1959.

Boyle and Smith share one half of the 2009 Nobel Prize in Physics for their invention of the charge-coupled device (CCD) used to generate high quality images in electronic form. The first two papers, one theoretical and one experimental paper appeared in the same issue of Bell Systems Technical Journal [W.S. Boyle and G.E. Smith, 49 (1970) 587; G.F. Amelio, M.F. Tompsett and G.E. Smith, 49 (1970) 593.]. A CCD can record a scene by accumulating light-induced charges over its semiconductor surface, and by transporting them to be read out at the edge of the light sensitive area. The invention utilized the properties of the then new MOS (Metal Oxide Semiconductor) technology to create an integrated and simple device to record and read out a scene. The read-out is similar to a fashion often referred to as a "bucket brigade" as it shifts arrays of information by successive site shift. The term "bucket brigade device" was coined by G. Krause in 1967 and the term had been used already by W.J. Hannan for the concept of transferring charges along a chain of semiconductor devices. F. Sangster patented in 1967 and published in 1969 with K. Teer [IEEE J. of Solid-State Circuits, SC-4 (1969) 131] what today is known as the bucket brigade device (BBD), where charges are transferred between successive capacitors by means of transistors in a way that transfers the signal to the second neighboring capacitor in one clock cycle. The crucial property that limits the length of chain is the efficiency of the charge transfer. The CCD, which was conceived in 1969, utilizes a different and more efficient principle, where "charge bubbles" created by light are semi-continuously flowing along the chain. CCD rapidly took over the development of solid-state devices for electronic image formation.

The use of "charge bubbles" mentioned above is not accidental. Actually, Boyle and Smith were spurred to compete with the, at the time, popular magnetic bubble memory at Bell Labs. A quote from a section in a recent review by Smith one finds [Nuclear Instruments and Methods in Physics Research A, 607 (2009) 1-5] reads:

> "To understand the importance of this device [magnetic bubble memory], one must look at the structure of the Electronics Division at Bell Labs, which was under Vice President Jack Morton. This was split into two divisions, one for semi-conductor devices and one for all others. Bill Boyle was Executive Director of the semiconductor part and I was a Department Head under him. Jack Morton was anxious to speed up the development of magnetic bubbles as a major memory

technology and was planning to transfer funds from Bill's division to the other where the bubble work was being done. For this not to happen, Morton demanded that Bill's division should come up with a semiconductor device to compete with bubbles. To address this demand, on 17 October 1969, Bill and I got together in his office. In a discussion lasting not more than an hour, the basic structure of the CCD was sketched out on the blackboard, the principles of operation defined, and some preliminary ideas concerning applications were developed. The train of thought that evolved was as follows.
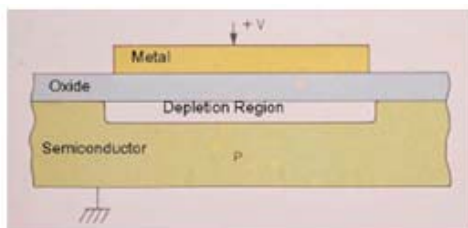

Fig. 1. The basic MOS structure

First, the semiconductor analogy of the magnetic bubble is needed. The electric dual is a packet of charge. The next problem is how to store this charge in a confined region. The structure that came to mind was a simple MOS capacitor in depletion ([Fig. 1]; the MOS capacitor structure is the principal element of the second contributing and strongly pursued technology, MOS integrated circuits.)"

The CCD is a metal-oxide semiconductor (MOS) device that can be used as a detector to record images in electronic form, and thus it offers a modern alternative to the photographic film. The surface structure of the CCD is made as a matrix of a large number of light-sensitive small cells, or pixels, arranged horizontally in rows and vertically in columns (Fig. 2). The pixels comprise MOS capacitors (which would correspond to the grains of the photographic film). When a photon of light impinges upon the area defined by one of the pixels it will be converted by the photoelectric effect[1] into one (or several) electrons that are stored in the capacitor. The number of electrons collected in the different pixels will be directly proportional to the light intensity at each pixel. Thus, the distribution of charge in the pixels is an analog representation of the image. By reading out the contents of the different pixels using successive charge shifting one can reconstruct the image (Fig. 2).

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[1] Photons can liberate bound electrons by the photoelectric effect. The bandgap of silicon is 1.14 eV, and photons with energy above that can liberate electrons. A. Einstein received the 1921 Nobel Prize in physics for explaining the photoelectric effect.
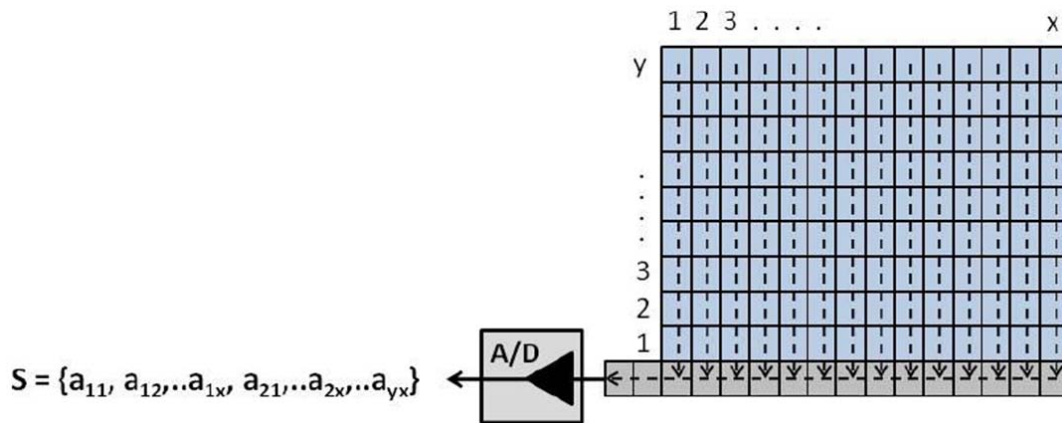
Fig. 2. The principle behind read-out of a CCD chip. One row at a time is shifted through an A/D converter which makes the output signal digital.

The CCD is manufactured on a silicon wafer by a large-scale integration process including a series of complex photolithographic steps. The silicon substrate is doped, usually with boron, to form p-type silicon, a material in which the main carriers are positively charged electron holes. Usually the photoactive layer is an epitaxial (layer-by-layer) grown layer on top of heavily p-doped silicon. The front side of the device hosts gate electrodes and the surface channel (oxide) layers, whereas the back side is bulk silicon, usually with a thin metal layer[2]. The anatomy of the CCD is such that it integrates the image recording capability with simple and efficient read-out. The read-out function can also be described in terms of an analog shift register that transports analog signals in a semi-continuous way, controlled by clock signals.
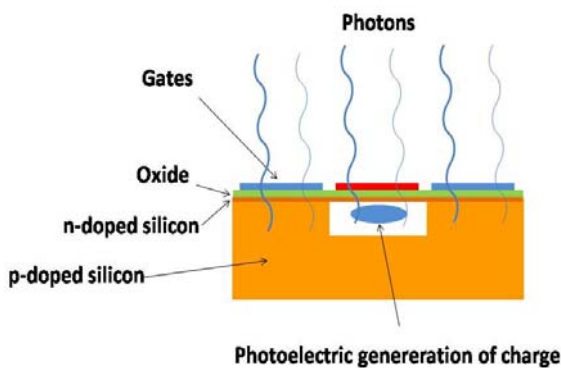

Fig. 3.
A MOS capacitor used as a light sensitive device.

The surface structure of the CCD is not formed by the silicon itself being arranged into individual pixels, but the pixels are defined by the position of electrodes (gates) on the CCD surface. When a positive voltage is applied to an electrode, all of the negatively charged electrons will be attracted to the area beneath the electrode (Fig.3). At the same time, positively charged holes will be repelled from the electrode area, forming a "potential well" (located deep within the silicon in an area known as the *depletion layer*, see Fig.1) in which all the electrons produced by incoming photons will be stored. With

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[2] In a special back side illuminated device, the thickness of the device is thinned from the back side in order to reduce absorption in the gate structures and thus increase sensitivity. This is particularly important for wavelengths that are subject to strong absorption, such as vacuum ultraviolet radiation.

increased exposure to light the potential well under the electrode will increasingly attract electrons until the potential well is full (often called *full well capacity*). To avoid overexposure the light must be blocked before this happens. This can be accomplished either by using a shutter as in a camera, or by fabricating the CCD so that it has inactive areas to which the contents of the pixels can be rapidly transferred awaiting read-out while the active part of the CCD can continue to collect light. Methods used are *full frame*, when the charge holding region is completely integrated with the light sensing region, and light is collected over the entire imager simultaneously. This allows almost the entire area to collect light (close to 100% fill factor). But to transfer and store the image, one then needs a physical shutter; a *frame transfer*, where light is collected over the entire imager and rapidly transferred to a charge holding area of equal size; from this light shielded area, the image can be read out while the next one is being collected; an *interline transfer* where there are light shielded CCD columns adjacent to the active ones, with rapid transfer and read-out of the charge. This means a lower fill factor, but certain compensations can be made using small lenses.

In early CCDs charge flowed along the Si-Si oxide interface, so called *surface channel CCD*. This limited the charge transfer efficiency because of charge trapping at interface states. In most modern CCD devices, certain areas of the surface of the silicon are n-doped, usually by phosphorous ion implantation in order to avoid charge being trapped in surface states, and to define the channels in which the charge packets will travel below the interface during read-out (so called *buried channel devices*). The gate electrodes are usually made of polysilicon, which has suitable properties regarding conductivity and transparency. The gates are deposited on top of the silicon oxide, which in turn is grown on top of the silicon substrate. In order to prevent charge spreading between adjacent pixel columns one introduces *channel stops* which are strongly p-doped regions.
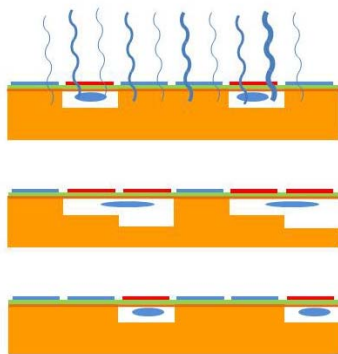

Fig. 4. The sequence of collecting and moving the charge along a column of a CCD detector. The charge generated by photons is forced to move one step at a time through the application of voltage pulses on the electrodes.

The read-out of the CCD is made by applying pulse trains to the electrodes. Each pixel is covered by several electrodes, typically three as shown in the figure although only one electrode is required to create the potential well that stores the charge. The other two electrodes are used for the charge transfer process by applying a three-phase voltage source. Fig. 4 illustrates the sequence for the movement of the charge one step along the columns of the CCD. By repeating this cycle, charge is transferred down the columns to eventually end up in a terminal row which is read out serially and perpendicularly to the columns. The serial read-out of each of the rows along the edge of the CCD is made such that each

charge packet in turn is amplified and converted to digital form. Thus, the entire content of the CCD is converted into an array of numbers representing the integrated intensity of each pixel. This array of numbers can readily be used to reconstruct the image recorded by the CCD.

In order to record color images filter techniques are used. A common type is named Bayer filter and it is a mosaic color filter array for arranging RGB color filters on a grid of photosensors. The filter pattern is 50% green, 25% red and 25% blue, owing to the sensitivity of the human eye (Fig. 5). The technique requires effectively 4 pixels for each resolution element, which restricts the detector resolution by this factor 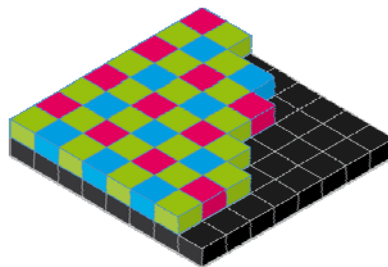compared to a black and white detector. Improved color schemes exist, e.g. using a dichroic[3] beamsplitter and several CCDs one achieves higher sensitivity. For scientific imaging, a large number of filters may be used in order to record spectroscopic information. The sensitivity of a CCD depends on the wavelength and the type of device. The *quantum efficiency* is the probability that an electron be produced by the photoelectric effect from an impinging photon. CCDs have high quantum efficiencies with values approaching 90%.

Fig. 5

An important property of an imaging detector is its *dynamic range*, i.e. its ability to image very bright and very faint light sources at the same time. The dynamic range is determined by the ratio between the *full well capacity* and the noise level. A common figure for the full well capacity is over 10^5 electrons, and the read-out noise level is a few electrons, so that the dynamic range can be of the order of 50000.

The resolution of a CCD is determined by the size of the pixels. Typical pixel sizes are 10 microns and even 1-2 micron CCDs are possible to fabricate. Regarding sizes 2048x2048 pixels CCDs are standard today.

The hour long discussion between Boyle and Smith in 1969 that was referred to earlier led to an enormous development of practical and scientific instrumentation based on CCDs: digital cameras, medical devices and high performance scientific instrumentation, not least for astronomy and astrophysics. These will be discussed below after a section regarding another important solid-state image sensor technology, the CMOS image sensor.

CMOS stands for complementary MOS (transistor) technology, where an n- and a p-channel device are used together to provide logic circuitry with very low power consumption since energy is necessary only during the switching process, e.g. from a "zero" to a "one". CMOS technology is the key to the very large integrated circuits available today. (The Nobel Prize in Physics the year 2000 was awarded to Jack Kilby for his part of the invention of the integrated

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[3] Dichroic means that different colors are refracted differently so that they can be physically separated.

circuit). CMOS was invented in the 1960's and CMOS sensors appeared by the end of the same decade, where the charge generated in a photosensitive sensor reversed biased pn-junction was read by a CMOS circuit. In CMOS image sensors each pixel is read individually and addressed like in normal integrated circuit arrays. Since each pixel is required to have several transistors (two or more) and not only a light sensitive area, CMOS pixels are larger than CCD pixels. Also other factors like lower noise and higher sensitivity still often make CCD the natural choice for high performance digital cameras and in most medical and scientific applications.

Fig. 6. A multi-megapixel camera CCD chip.

CCD image sensors have found important applications in many areas of society and science. They are found e.g. in digital cameras, scanners, medical devices, satellite surveillance and in instrumentation for astronomy and astrophysics. There are tens of thousands of scientific publications that mention the use of CCDs and many millions of digital cameras that use CCD sensors. Astronomy with astrophysics has become a significant application area for CCDs. One of the largest CCD imagers built for scientific applications (for PAN-STARRS, the Panoramic Survey Telescope and Rapid Response System, in Hawaii) contains several cameras consisting of mosaics of CCD chips with a total of over 5 gigapixels.

As already stated, the applications within astronomy are scientifically very important. The Hubble Space Telescope is equipped with several CCD cameras for different purposes,
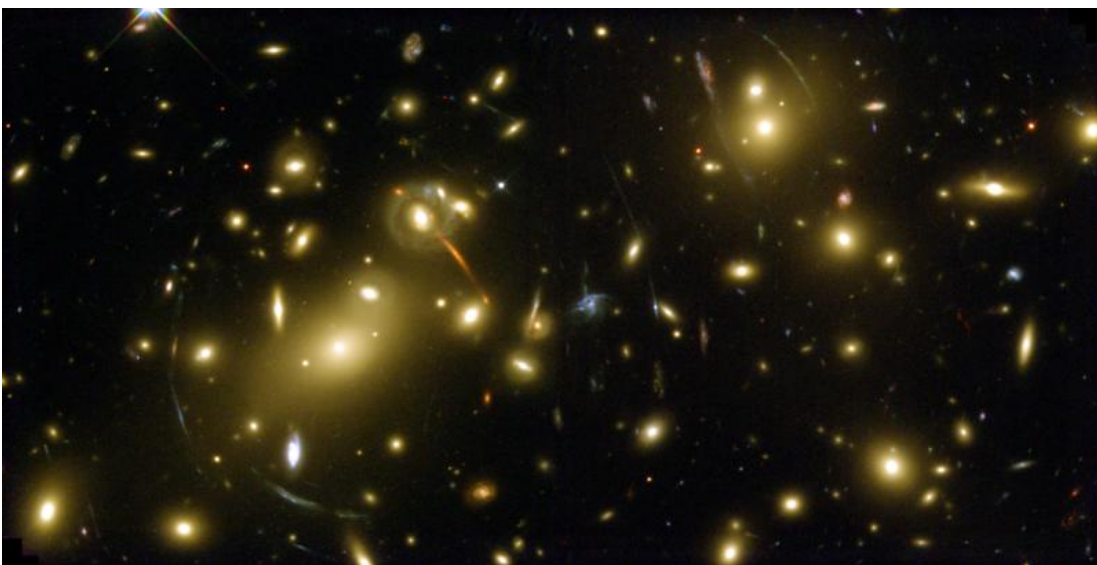

Fig. 8. The galaxy cluster Abell 2218. *Image: WFPC2, Hubble Space Telescope, NASA.*

one example being the Wide Field Planetary Camera (WFPC), which was recently upgraded to its third version. The figure above shows a spectacular image of a galaxy cluster (Abell 2218) taken in the year 2000 with WFPC2. The faint ring-like objects seen in the picture are gravitationally lensed background galaxies, which have been used, for instance, to estimate the total mass of the cluster, giving evidence for the existence of large amounts of dark matter.

There are several important medical applications for CCD cameras, e.g. for the study of tissues and cells as imaging devices in microscopes or for the recording of cells and tissue in situ, where image processing allows a medical doctor to spot minute deviations from normality. CCDs are used not only for direct imaging but also to record fluorescence images from stained tissues and cells. Digital photography has also revolutionized almost all image based medical diagnostic tools. A large application is found in endoscopy for inspections inside the body and for guidance during micro- or 'key hole'- surgery. There are many types of endoscopes, e.g. based on single optical fibers, optical fiber bundles or in the form of capsules possible to swallow with built in light source, CCD sensors and wireless signal transmission. Endoscopes also have many industrial applications. Recently lense-less measurement systems have been developed for biosensing purposes, where a direct cell recording is made by sampling the flow through a micro fluidic chip. This may be one of the new niches for high resolution digital imaging.

Solid-state image sensors and digital cameras have changed the role of images in our society, since they give electronic signals, digits, which can easily be transmitted and treated. In science, the possibility of transferring and processing images digitally is a real revolution. Digital image processing is now a global commodity which enables, for instance, the best international expertise to be involved in crucial diagnostic and even surgical situations, through remote control and feedback through digital cameras. Furthermore the evaluation of large amounts of data (e.g. created in mapping the universe) can be spread to many groups and even to volunteers from the general public.

Useful reading

1. W.S. Boyle and G.E. Smith, *Bell Systems Technical Journal* <u>49</u> (1970) 587; G.F. Amelio,
M.F. Tompsett and G.E. Smith, *ibid.* <u>49</u> (1970) 593.
2. J.R. Janesick: *Scientific Charge-Coupled Devices* (SPIE Press, 2001).