The Millennium Technology Prize Laureate 2010

"For his contributions in the area of plastic electronics. His work is leading to a variety of products with high energy efficiency and reduced environmental impact. Polymer-based materials are bringing about a revolution and paradigm shift in the optoelectronics sector, with far-reaching consequences for applications in display devices, lighting, sensing and solar energy harvesting. "

Professor Sir Richard Friend

Cavendish Professor of Physics, the University of Cambridge, United Kingdom

Born January 1953 in London, United Kingdom.

Timeline

1988	Polymer field-effect transistor demonstrated
1990	Polymer LEDs demonstrated
1995	Efficient polymer photovoltaic diodes demonstrated
2000	World's first full color ink-jet printed PLED display
2009	Google, Nokia, Samsung selling millions of phones with touch OLED screen, first OLED lighting panel

Developer of plastic electronics

The 2010 Millennium Technology Prize Laureate Sir Richard Friend's initial innovation, organic Light Emitting Diodes (LEDs), was a crucial milestone in plastic electronics. He showed a method to use polymers as solution processed semiconductors. Electronic paper, cheap organic solar cells and illuminating wall paper are examples of the revolutionary future products his work has made possible.

In electronic devices different materials have different functions. Traditional electronics rely on inorganic conductors such as copper and doped silicon. Copper wires conduct electricity; silicon semiconductor chips do the computing. Polymer plastics are generally insulators, blocking the passage of electrical current. They are an excellent choice for around wires to prevent short circuits, or to shape mobile phone covers. Or so traditional thinking would suggest.

Today many new phones have touch OLED screens. OLED stands for Organic Light Emitting Diode, made of conductive plastic material. The material is called "organic" because the polymers used are carbon-based, much like living organisms. Soon we may see 100 inch highdefinition TV-sets, which are only few millimetres thick and can be rolled up when not in use, or paper-thin, inexpensive lighting panels covering the whole wall. Electronic components based on polymers have made these applications possible.

Friend's inventions were landmark achievements in the rise of plastic electronics. In the late Eighties, his research group discovered that conjugated polymers behave in many respects like inorganic semiconductors and can be used in a number of semiconducting devices.

Thanks to their pioneering discoveries, plastic electronics has now developed into a large international research field with significant academic and industrial activities. Polymer LEDs are already used in small displays, and energy-efficient lighting applications are being developed. Polymer photovoltaic diodes promise to enable very low cost solar cells. Printed polymer transistors enable new electronic applications such as flexible and transparent displays.
An important characteristic of plastic electronics is the simplicity of the method used to produce them. Inorganic transistors require massive vacuum systems and complex manufacturing processes. However, the organic polymer materials Friend used can be dissolved in organic solvents to create "inks" that can be used to create circuits simply by printing them under normal atmospheric conditions.

It is easy to understand the global electronics industry's huge interest in organic and solution processable semiconductor technology. The ability to apply low temperature, low cost transistors and LEDs to flexible materials using a process that could be as simple as painting can enable new products that, until now, were unfeasible.

A Flexible OLED Display driven by organic transistors

Plastic as a semiconductor

It is generally accepted that inorganic metals conduct electricity well and that organic compounds, for example, plastics, are insulating. Plastics are polymers, molecules forming long chains, repeating themselves again and again. In 1977, **Alan J. Heeger, Alan MacDiarmid** and

Hideki Shirakawa found out that a thin film of polyacetylene could be oxidised with iodine vapour, turning the material into a conductor. This sensational finding earned them the 2000 Nobel Prize in Chemistry.

To make a polymer material conductive its electrons need to be free to move and not bound to the atoms. The first condition for this is that the polymer consists of alternating single and double bonds, called conjugated double bonds. By doping conjugated material with iodine it becomes electrically conductive.

Researchers were intrigued by conductive polymers because of their desired properties: combining flexibility and elasticity of plastics with high electrical conductivities of metals was a tempting idea. However, in the Eighties, the future for conjugated polymers looked very limited. They seemed ill-suited for further commercial development and their conducting properties were not living up to their billing as 'synthetic metals' for mainstream uses. They have nevertheless found some important niche applications.

In the mid-Eighties Friend started a programme to research the use of these polymers, but he was more interested in their semiconducting nature. "We had success in making transistors, and were able to show that they performed well, but the polymer we used at that time was not very stable."

The second semiconductor device was a real success. An LED is a simple semiconductor light source used as indicator lamps in many devices, and increasingly for lighting. Instead of using inorganic semiconductor as a light emitting material of LED, Friend and his colleagues used polymer. Their first, most basic organic LED consisted of a single organic layer of poly(p-phenylene vinylene). In an organic LED, the light emitting electroluminescent layer is composed of a film of organic compounds. This layer of organic semiconductor material is formed between two electrodes, where at least one of the electrodes is transparent. In operation, voltage is applied across the electrodes, creating an electric field and injecting charges into the polymer where they recombine and emit light.

There is often a big step between the first chemical synthesis of a molecular substance and the development of processing methods for practical applications. Friend's group was not the first to produce LEDs from organic materials. In 1980, Eastman Kodak Company researchers had produced the first organic LEDs, made out of unlinked organic molecules, and this approach has been successfully developed since then. Nevertheless, the conjugated polymer material Friend used, had an advantage over their unlinked counterparts: dissolved in a chemical solvent, they can be printed into circuits with an inkjet printer. Most of the unlinked carbon-based molecules, including first organic LEDs, needed to be deposited on a circuit board in a vacuum.

Solution-processable manufacturing process meant polymers could be produced quickly and cheaply. The Cambridge researchers boldly wrote in their Nature article in 1990: *"...The combination of good structural properties of this polymer, its ease of fabrication, and light emission*

in the green-yellow part of the spectrum with reasonably high efficiency, suggests that the polymer can be used for the development of large-area light-emitting displays."
Exactly that has happened. Their highly cited paper was followed by a gold-rush in plastic electronics.

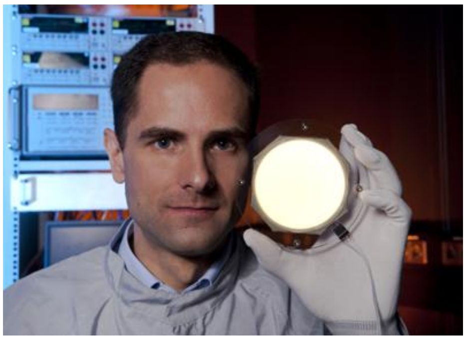
Wide applications

While plastic electronics is still taking its first commercial steps, there are numerous innovative products under development. OLED displays are already used in MP3-players, mobile phones and some laptops. Device manufacturers are attracted by OLED technology's low power consumption and picture quality. Unlike traditional LCD screens, OLED does not require backlight because of the self luminous polymer diodes. It means lower power consumption and larger viewing angle, but OLED screens are also brighter and have a superb colour reproduction. They are readable even in direct sunlight.

Plastic Logic, one of the two companies Friend and other Cavendish Laboratory researchers started to commercialise their inventions, has recently announced the QUE eReader. This ultra-thin gadget is the first to use transistors based on organic polymers rather than silicon. Transistors are needed on the screen's backplane to drive the pixels correctly. Organic transistors make it possible to use a plastic backing instead of glass, resulting in a reader that is thin, flexible, lightweight, and extremely durable. Durability has been demonstrated by dropping the reader on concrete, and it survives.

OLEDs are also used in television screens. Asian electronics giants have unveiled televisions only three millimetres thick using this technology. OLED televisions are considered brighter and more energy-efficient, and they have better refresh rates and contrast than LCD or Plasma televisions. OLED display can even be made transparent.

Organic polymer solar cells could cut the cost of solar power by making use of inexpensive organic polymers rather than expensive crystalline silicon. Polymer cells can be made with a power conversion efficiency of seven percent which is still somewhat lower than that of dye-sensitised or silicon solar cells. However, the performance is steadily improving, and polymer solar cells promise to enable much lower production costs due to the ability to solution coat the active layers.



In 2009 OSRAM started to sell their first OLED panel. Round panel, 88mm in diameter, offers 25lm/W efficiency.

Plastic electronics components are well suited for printed electronics, use of printing methods to create electrically functional devices. Printed electronics is expected to facilitate widespread and very low-cost electronics, such as large flexible displays, smart labels, decorative and animated posters, and active clothing.

This manufacturing method is also attractive from an environmental perspective. With the methods used to manufacture conventional inorganic electronics, only a few percent of the materials are actually used. Printing is far more efficient, and by optimising the method it is possible to achieve usage rates as high as 90 percent.

First steps to innovation

Friend became familiar with the world of organic conductors in 1977, while working at the Université Paris-Sud in France. He had always been intrigued by the science and engineering that lies at the boundaries of physics, chemistry and material science.

At Cambridge University in the late Eighties, Friend and his researchers were constructing semiconductor devices with silicon-like properties, but made of plastics. His PhD student Jeremy Burroughes was working on a project developing an understanding on how organic conjugated materials behave within electronic and optoelectronic devices. "We noticed polymers didn't work like silicon. When we put electron to polymer chain, it actually changes shape, and colour," Friend says.

In 1988 they succeeded in making the first polymer FET-transistor, showing very good transistor characteristics, even though the polymers were too disordered to work. The research was reported in Nature, without major hype.

Later, while measuring the electrical properties of a plastic semiconductor material, they discovered a totally unexpected property. A piece of semiconductor material was sandwiched between two metal layers. While voltage was applied across the electrodes, researchers spotted that green light was coming out of the polymer material. "It was good fortune that top electrode was thin enough, it was semitransparent," Friend recalls.

Their first organic polymer LED came into existence, partly by accident. Friend, PhD student Burroughes and Donal Bradley recognized immediately the significance of their results. "We must have been modern academics at that time, because we rushed to find out how to patent it."

It became evident that they had to pay patent costs by themselves. In those days, the university did not have a resource to cover such expenses. Their polymer-based LED was patented in 1989 and in October 1990 the findings were reported in Nature.

James Clerk Maxwell and Friend

Becoming a scientist was never a hard choice for Friend. "I knew I was going to be a scientist from the age of five or six. I just knew. It was such an obviously interesting space. "

At age of 10, he became familiar with the basics of modern electronics, building simple transistor circuits and radios. "It was so interesting: solder them together and sometimes get the components to do something useful."

Today he holds the famous Cavendish Professorship at Cambridge University. The Cavendish Laboratory (the University's Department of Physics) physics is known for its numerous Nobelists. The first Cavendish professor was James Clerk Maxwell, developer of electromagnetic theory.

Friend tells an anecdote about Maxwell, who began his famous inaugural lecture in 1873 by saying: 'It is generally considered that there is nothing left to do in physics.' Friend and Maxwell think differently. "There is everything to do; it is merely limited by our own imagination." It was a prophetic statement, because it was just before relativity and quantum mechanics.

Friend's inventions have taken him deep into potential applications. "I find myself being swept downstream to engineering. I feel I have to paddle upstream to get back to new ideas in science, where I probably sit best."

There is still a lot to investigate in the physical properties of polymer semiconductors. In Friend's thinking, 'messy' research areas, which are not well understood, are the most tempting. "If you go looking in places that others say are not worth looking at, you will probably find something good. If it is very unfashionable, you have to be brave to do it, but you probably have higher chance of being first."

New semiconductor devices

Friend's Optoelectronics group at Cavendish Laboratory continued to drive research and the development of polymer semiconductors after the initial transistor and LED innovations. The field has now developed into a large international research area with significant academic and industrial activities.

Friend's research group demonstrated new semiconductor devices, efficient photovoltaic diodes in 1995, optically-pumped lasing in 1996, and directly-printed polymer transistor circuits in 2000. As well as developing technology, the group has made progress in understanding the underlying science of organic electronics.

The research group is also exceptionally business oriented. They have commercialised their scientific discoveries through the formation of two spin-off companies: Cambridge Display

Technology is developing polymer LEDs technology for emissive, full-colour displays, and Plastic Logic is using organic transistors to enable flexible paper-like displays. The group recently announced plans for forming a third spin-off company to accelerate the development of polymer solar cells.

“Cambridge Display Technology started in 1992. It took quite a lot of our time, but it also turned out to give us engineering strength. It sustained our basic research in a way I did not anticipate. We had better materials, better know-how about making good devices.”

Bright future

The invention of polymer LED unleashed a huge level of international interest. Almost overnight there was a new research field. Giant companies like Siemens, Osram, Philips, Sony soon entered the field of polymer electroluminescense.

Today market research firms' predict exponential growth in many existing OLED products. According to Isuppli Corp, an upward momentum of OLED shipments for primary mobile phone displays is expected in coming years. They forecast that global shipments of OLED main mobile phone displays will rise to 178 million units in 2015, up from 22.2 million in 2009. In other words, the shipments will rise eightfold by 2015.

Konarka, a solar-cell startup company, has opened a commercial-scale factory, with the capacity to produce enough organic solar cells every year to generate one gigawatt of electricity, the equivalent of a large nuclear reactor.

Polymer semiconductors have become a flourishing technology, with a bright future ahead.

LINKS AND FURTHER READING

Publications

"Light-Emitting Diodes Based on Conjugated Polymers", J. H. Burroughes, D. D. C. Bradley, A. R. Brown, R. N. Marks, K. Mackay, R. H. Friend, P. L. Burn and A. B. Holmes, Nature 347, 539-541 (1990).

Links

Wikipedia article about plastic electronics http://en.wikipedia.org/wiki/Organic_electronics
Wikipedia article about organic LEDs http://en.wikipedia.org/wiki/Organic_LED
Optoelectronics Group, Cavendish Laboratory http://www.oe.phy.cam.ac.uk/

Companies

Cambridge Display Technology CDT http://www.cdtltd.co.uk/
Plastic Logic http://www.plasticlogic.com/
Konarka http://www.konarka.com/

Curriculum Vitae of Sir Richard Friend

Education

1971-4 Trinity College, Cambridge BA in Theoretical Physics, Class 1, 1974
1974-8 Research Student in the Cavendish Laboratory, Cambridge, Ph.D 1979 Research Fellowship, St. John's College, from May 1977

Current University Position

1995- Cavendish Professor of Physics, University of Cambridge
1977- Fellow, St. John's College, Cambridge

Other Employments/Consultancies

1996- Chief Scientist, Consultant, Cambridge Display Technology Ltd.
2000- Chief Scientist, Consultant, Plastic Logic Ltd.
2003 Mary Shepard B Upson Visiting Professor, Cornell University, USA

Previous Employment

1977-1980 Research Fellow, St. John's College, Cambridge
[March 1977 - March 1978. Attaché de Recherche du CNRS, at the Laboratoire de Physique des Solides, Université Paris-Sud, Orsay, France]
1980-1985 University Demonstrator in Physics, University of Cambridge
1985-1993 University Lecturer in Physics, University of Cambridge
1993-1995 University Reader in Experimental Physics, University of Cambridge
[July 1986 - Jan. 1987, Visiting Professor at the University of California, Santa Barbara. March - July 1987, Chercheur Associé au CNRS, Centre de Recherche sur les Très Basses Températures, Grenoble, France Oct. 1992- Oct. 1993 Nuffield Foundation Science Research Fellowship]
1980-1995 Teaching Fellow, St. John's College, Cambridge
1984-1986 Director of Studies in Physics, 1987-91 Tutor

1998-2003 Member, Technology Advisory Council, BP plc
1998-2007 Consultant, Epson Cambridge Laboratory

Prizes, etc.

1988 Charles Vernon Boys Prize of the Institute of Physics
1991 Royal Society of Chemistry Interdisciplinary Award
1993 Fellow of Royal Society of London
1996 Hewlett-Packard Prize of the European Physical Society
1998 Rumford Medal of the Royal Society of London
2000 Honorary Doctorate, University of Linkoping, Sweden
2001 Italgas prize for research and technological innovation
2002 Honorary Doctorate, University of Mons-Hainaut, Belgium

2002 Silver Medal, Royal Academy of Engineering, London
2002 McRobert Prize, Royal Academy of Engineering, London (awarded for engineering achievement by Cambridge Display Technology)
2002 Fellow, Royal Academy of Engineering
2003 Faraday Medal of the Institute of Electrical Engineers
2003 Gold Medal of the European Materials Research Society
2003 Knight Batchelor (Queen's birthday honours)
2003 Descartes Prize of the European Commission (coordinator of polymer LED project)
2004 Honorary Fellow of the Royal Society of Chemistry
2005 Jan Rachmann Prize of the Society for Information Display
2006 Honorary Fellow, University of Wales, Bangor.
2006 Honorary Doctorate, Heriot-Watt University
2007 IEEE Daniel E. Noble Award
2008 Honorary Fellow, Institute of Physics, London
2008 Honorary Degree, University of Nijmegan, The Netherlands
2008 Inaugural Award of the Rhodia-de Gennes Prize for Science and Technology, Paris
2009 Honorary Degree, University of Montreal, Canada
2009 Business and Innovation Medal of the Institute of Physics
2009 King Faisal International Prize for Science

Named Lectures

1997 Debye Lecture, University of Utrecht, The Netherlands
1999 Rochester Lecturer, Department of Physics, University of Durham
1999 Rolf Sammet Visiting Professorship, University of Frankfurt-Main
1999 H. H. Johnson Lecturer, Cornell University
2000 A. D. Little Lecturer, MIT
2001 Xerox Distinguished Lecturer, Toronto
2001 Engineering Lecture, University College of North Wales, Bangor
2004 Kelvin Lecture of the Institution of Electrical Engineers

Citations Identified by ISI as the most-cited UK-based scientist working in the physical sciences over the decade 1990-1999. Identified by ISI as one of the 2 most-cited physicists based in the UK

Publications

>700 papers etc. in scientific journals

Patents:

60 patents (issued), >40 (pending)