Technology LEDs

Light-emitting diodes hit the centenary milestone

Fred Schubert and Jong Kyu Kim guide us through 100 years of the LED, before predicting where our most promising light source will take us over the next decade.

British radio engineer Henry Joseph Round discovered the LED completely by accident. While investigating the electrical properties of a metal-semiconductor SiC rectifier, a device that offered a promising alternative to more-expensive vacuum diodes, he witnessed the first light emission from a solid-state material driven by an electrical current.

Round reported this "curious phenomenon" of electroluminescence in 1907 in a remarkably short publication of two paragraphs (figure 1), which detailed the yellow emission from a two-pole structure with an "unsymmetrical passage of current". Today this device would be called a diode, which makes Round's article the first ever report of an LED.

With hindsight we can see the scientific and commercial significance of such a discovery, but the phenomenon of electroluminescence was forgotten for several years. However, in 1923 it was rediscovered by a talented 20-year-old Russian scientist Oleg Vladimirovich Lossev, who produced the first photograph of electroluminescent light (see box, "The evolution of the LED"; Lossev, 1923). SiC was the material, in the form of a metal-semiconductor diode.

Lossev carried out detailed measurements of the diode's current-voltage characteristics and realized that forward and reverse biasing both produce emission (figure 2, p22). Today this can easily be explained because we know that impact ionization and minority carrier injection both generate light. Lossev, however, lacked this understanding and was puzzled about the origin of the luminescence. He wondered whether light was generated by heat glow (incandescence), and to test that theory he measured the evaporation rate of a droplet of liquid benzene placed on the luminous sample's surface. However, the benzene evaporated very slowly, which led him to deduce that luminescence was not caused by incandescence.

Armed with this knowledge, Lossev then postulated that the light came from a process that is "very similar to cold electronic discharge". He also showed that the emission could be switched on and off very rapidly, which would allow the device to be used in a light relay – a component that we would now call an optical communication source.

Lossev's was the first detailed study of semiconductor electroluminescence. In recognition of his accomplishments he was awarded the degree of Candidate by the Ioffe Institute in 1938, the equivalent of a doctorate.

White and blue LEDs are used to illuminate the keypads and backlights of billions of handsets, as well as to provide a flashlight for the accompanying cameras. According to Strategies Unlimited, sales into this market peaked at just over $2 billion in 2004 and were worth $1.8 billion last year.

The evolution of the LED

The LED has evolved from an object of curiosity to a product with annual sales of several billion dollars. The first photograph of electroluminescence from an LED was taken by Oleg Vladimirovich Lossev in 1924 (Wireless World and Radio Review 1924 271 93). It would be several more decades before colored LEDs were produced, which were first used as indicators. Carefully mixing these colors together produces white light. Today general illumination is seen as the next big market for the LED and companies such as Color Kinetics are producing products for this application.

A Note on Carborundum.

To the Editors of Electrical World:

SIRS:—During an investigation of the unsymmetrical passage of current through a contact of carborundum and other substances a curious phenomenon was noted. On applying a potential of 10 volts between two points on a crystal of carborundum, the crystal gave out a yellowish light. Only one or two specimens could be found which gave a bright glow on such a low voltage, but with 110 volts a large number could be found to glow. In some crystals only edges gave the light and others gave instead of a yellow light green, orange or blue. In all cases tested the glow appears to come from the negative pole, a bright blue-green spark appearing at the positive pole. In a single crystal, if contact is made near the center with the negative pole, and the positive pole is put in contact at any other place, only one section of the crystal will glow and that the same section wherever the positive pole is placed.

There seems to be some connection between the above effect and the e.m.f. produced by a junction of carborundum and another conductor when heated by a direct or alternating current; but the connection may be only secondary as an obvious explanation of the e.m.f. effect is the thermoelectric one. The writer would be glad of references to any published account of an investigation of this or any allied phenomena.

NEW YORK, N. Y. H. J. ROUND.

Fig. 1. (above and left) Henry Joseph Round, a prolific inventor who filed more than 100 patents, published the first ever report of electro-luminescence in 1907 in the journal Electrical World (1907 19 309).

The first modern, correct interpretation of light emission from a p-n junction was provided by Kurt Lehovec and colleagues at the Signal Corps Engineering Laboratories in New Jersey in 1951. They claimed that the luminescence came from minority carrier injection across the boundary of a p-n junction under forward bias (figure 3, p22).

Companies flock to LED development

Since then, LED developments have flourished, with remarkable improvements in device characteristics continuing to this day. These advances were kick-started by replacing SiC with more efficient materials based on III-V compounds. Key milestones include the demonstration of single-crystal GaAs (Welker, 1952), which provides the ideal substrate for many devices. This platform was used for the initial development of GaAs LEDs and injection lasers, which was led by General Electric in Schenectady, IBM in Yorktown Heights and Lincoln Laboratories in Lexington. It was not long before these three, all located in the northeast of the US, were competing with the then-famous Bell Telephone Laboratories in Murray Hill and the RCA Laboratories in Princeton, in an LED development race.

The first visible LEDs based on III-V materials were built in 1955 by Wolff and colleagues at the Signal Corps Engineering Laboratories. This orange-emitting GaP device generated light through the impact ionization of carriers at the metal-semiconductor junction. However, the lack of a p-n junction meant that it was too inefficient and unsuitable for commercialization.

LED progress followed through the development of new red-, yellow-, orange- and green-emitting materials in the 1960s and 70s, which were made from III-V compounds, such as GaPAs, nitrogen-doped GaP, nitrogen-doped GaPAs, and zinc and oxygen-doped GaP. These LEDs were far more efficient than Wolff's metal-semiconductor structure but they still fall well short of the performance of today's equivalents employed in high-power applications, which are based on AlGaAs and AlGaInP.

Developing and improving these devices required a great deal of effort but they were still an easier nut to crack than the blue LED. Work on this type of emitter began in the late 1960s at RCA, and in 1969 Paul Maruska made the first breakthrough: a single-crystalline GaN film. However, these films were unintentionally n-doped and the addition of p-type dopant only produced insulating material. The lack of p-doped material led the team to build metal-insulator-semiconductor diodes, but such devices are inevitably inefficient and this project was abandoned in the early 1970s.

The following decade was a lean time for GaN LED research. However, in 1989 Isamu Akasaki and co-workers from Nagoya in Japan produced the first p-type doping and conductivity in GaN using magnesium doping activated by electron-beam irradiation. An LED with 1% efficiency followed three years later, but this was soon surpassed by Shuji Nakamura from Nichia, who managed to fabricate blue and green GaInN double-heterostructure LEDs that were 10 times as efficient. Further improvements have continued to this day, with the latest devices producing hundreds of milliwatts.

Improvements in all forms of LED have also been spurred on by MOCVD, which superceded approaches like liquid-phase epitaxy, which cannot produce uniform epilayers just several nanometers thick. The greater control led to double-heterostructure designs in the 1970s and quantum-well structures in the following decade, which provide greater confinement and boost device brightness. Commercial MOCVD tool development has also cut LED manufacturing costs, thanks to an increase in the number of wafers that can be loaded into a growth run.

The tremendous hikes in efficiencies and output powers of all of these colored LEDs have dramatically increased the number and variety of applications that they can serve.

However, current interest in single-color LEDs is overshadowed by their white cousins, which are starting to unlock the door to more lucrative markets, such as general illumination. One approach to producing white light involves the mixing of emissions from several different-colored LEDs (see box "The evolution of the LED"). However, the dominant commercial method that was pioneered by Nichia, which is simpler and produces a high color-rendering index, involves a yellow phosphor and a blue LED chip (figure 4a, p22). The blue-emitting

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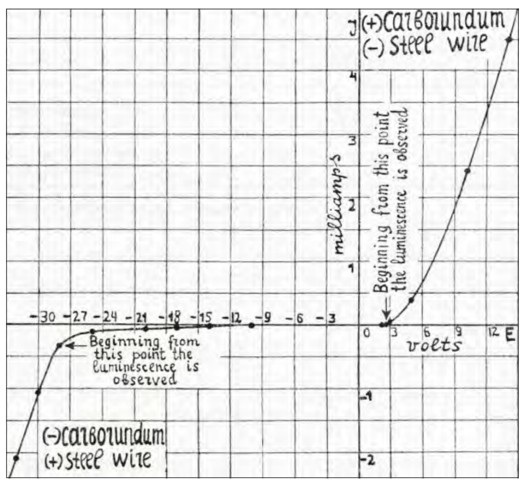

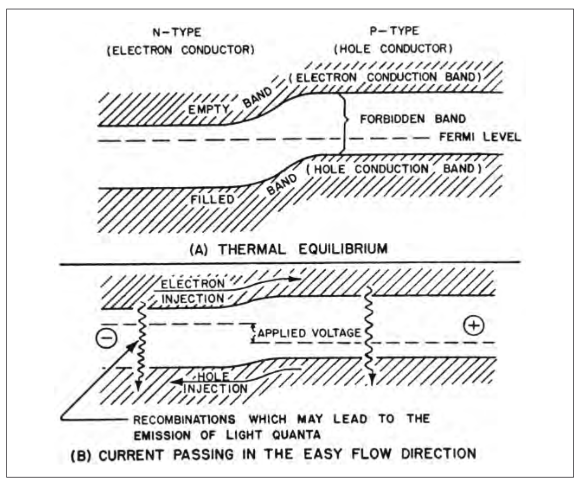

Fig. 2. (left) Lossev was keen to understand how the LED works and spent time recording the current–voltage characteristic of a SiC device. His labels reveal that electroluminescence occurs under forward and reverse bias (1928 Philosophical Magazine 6 1024).
Fig. 3. (right) Lehovec and co-workers were the first to explain the principles of LED operation. They revealed the band structure under thermal equilibrium and forward bias, which they referred to as the easy-flow direction (1951 Physical Review 83 603).

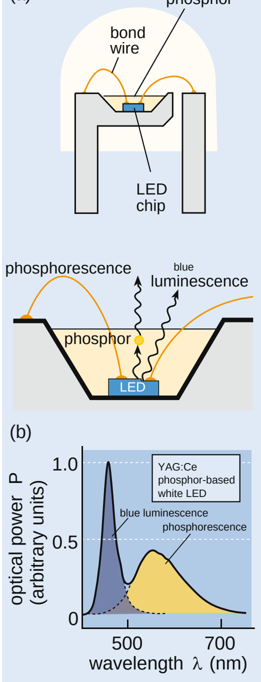

Fig. 4. white-light LEDs produce their emission by using a blue galnn chip to pump a wavelength-converting phosphor.

chip excites the yellow-emitting phosphor and white light is created from mixing these two sources.

The white LED is the major battleground for today's chip makers, which have driven significant improvements in white LED output. Values of 100–150 lm/W have been reported during 2006 and 2007. This compares favorably with incandescent and compact fluorescent lamps, which have luminous efficacy figures of 15 and 70 lm/W, respectively.

The advantages that would come from a switch from incandescent and fluorescent lamps to highly efficient solid-state sources have been well documented, and these include energy and financial savings and a reduction in the use of mercury. The energy savings could be substantial and even lead to 280 major electrical power plants being switched off. LEDs are also beginning to provide the backlighting source for liquid-crystal displays (LCDs) used in televisions and computers. Here, the new source not only cuts power consumption but also produces a greater color gamut than a fluorescent lamp and a reduction of motion artifacts.

So far we have ignored one other aspect that fundamentally distinguishes solid-state sources from their conventional cousins – greater controllability. Scientists and engineers that strive to control and tune all of the properties of an LED have the unprecedented challenge of constructing light sources that can be controlled in terms of spectrum, polarization, color temperature, temporal modulation and spatial emission pattern. Some of these properties are relatively easy to control, such as the optical spectrum, but innovative ideas are needed to improve the control of properties such as polarization.

With LEDs on the road to becoming the dominant and most versatile light source available, controlling the emission properties will become increasingly important, particularly because this will help the technology to differentiate itself from existing competition. In turn, new classes of benefits based on the enhanced functionality will start to emerge.

Examples of such benefits include LCDs lit by linearly polarized sources. This would remove polarizers from displays that discard a significant proportion of light and create a more efficient product. Meanwhile, a switch to LEDs for general illumination would allow indoor lighting with controlled brightness and color temperature. This could accurately mimic the natural changes in outdoor light that occur during the day. Since the human daily cycle and the wake-sleep rhythm are driven by changes in sunlight, using LED-based light that can replicate this source could improve the well being of everyone.

LEDs could also feature in various transportation applications to provide additional information to visual signals. A red LED traffic light could, for example, transmit an encoded signal that tells an intelligent car to stop. This would cut the number of accidents caused by inattentive and impaired drivers running a red light.

A century has now passed since Round stumbled across the SiC rectifier crystal, which unexpectedly emitted light. The intervening years have seen breathtaking progress and created a billion dollar market for the LED, but we are still a long way from utilizing the full capability of this device. The journey is not over – in fact, it's hardly begun. •

Further reading

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