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Bergh A A & Dean P J. Light-emitting diodes. *Proc. IEEE* **60**:156-224, 1972.
[Bell Telephone Laboratories, Murray Hill, NJ and Royal Radar Establishment, Malvern, England]

Light-emitting diodes (LEDs) are devices designed to efficiently convert electrical energy into electromagnetic radiation, most of which is visible to the human eye. Some of the disciplines involved in the understanding and utilization of LEDs are reviewed, with emphasis on the III-V semiconducting compounds and GaP LEDs in particular. Salient features of photometry, the physics of electrical injection and luminescence, and the design of LEDs are discussed in detail, followed by a survey of prominent applications for the various LEDs. [The *SCI*® indicates that this paper has been cited in over 160 publications since 1972.]

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"By the late 1960s, Bell Laboratories was involved in a large program of development work aimed at the manufacture of light-emitting diodes (LEDs). These new light sources, by then receiving attention in many other institutions in North America and overseas, were a by-product of materials research that had become increasingly intense during the previous decade. Earlier hopes for electroluminescent (cold) light sources had largely centered upon materials such as the wider bandgap II-VI compounds. These materials make excellent cathode-ray-tube phosphors, but proved very intractable in the form of low-voltage electroluminescent light sources. The new initiative in the 1960s concentrated upon the III-V compound semiconductors. These materials are less ionic, have generally more stable electrical properties, and readily exhibit ambipolar conductivity. Their band gaps, however, are only marginally adequate to cover a major fraction of the visible spectrum. The preparation of a high-quality LED demands good p- and n-type conductivity, the presence of a suitable luminescence activator, adequate control of competitive recombination pathways, good mechanical and optical properties of the electrical contacts, proper passivation of the semiconductor surface, and good maintenance of all properties under quite high densities of recombination local to the junction during device life.

"Certain of these requirements were met through new insights into the properties of semiconductors; for example, the understanding of the importance of the isoelectronic trap as a luminescence activator, particularly for indirect-gap semiconductors, through the study of non-radiative (Auger) recombination. The exploitation of isoelectronic traps abrogated the previously existing rule that useful LEDs were less dramatic, depending upon advances in metallurgical and electronic knowledge of GaP, GaAs, and their ternary alloys.

"The gathering evidence that many difficulties were becoming sufficiently mastered by the late 1960s heightened interest in reviews of the subject. The fact that the successful developments had depended upon advances across such a broad front—metallurgy, electronics, chemistry, physics, and engineering—raised obvious difficulties for prospective reviewers. Bell Laboratories received a request for such a review from the IEEE in late 1969. The authors were separately approached through their local managements, and both initially declined as a consequence of their assessment of the magnitude of the task! At that time, initial steps were being taken to establish an LED manufacturing capability at Western Electric in Reading, Pennsylvania, with advanced development work at the co-located branch of Bell Laboratories. This required many technical meetings involving people from the research and primary development departments at Murray Hill. The authors, representing two different organizations, i.e., research and exploratory development, were traveling together to one such meeting in very bad winter weather in 1970. The idea of coauthorship of the review on LEDs came directly out of a conversation held during a long traffic jam on the ice-bound Interstate Highway 78!

"The uses of LEDs have become very familiar since the article was first conceived. Some of these have come and gone under the impact of competition from passive displays much more suitable for miniature battery-powered equipment. However, the jewel-like charm of LED displays has ensured their continued presence in many less power-critical applications. As in the more recent liquid-crystal displays, severe price competition set in at an early stage, and evolution among the producers was consequently rather rapid. The center of production capacity of both types of display has exhibited a significant shift toward the Far East. The current situation may represent a plateau of relative stability for small numeric displays. While the thrust of development for liquid crystals shifted toward large color displays, long wavelength LEDs secured a significant position in the rapidly expanding technology of lightwave communication.

"An expanded version of this paper appeared in book form in 1976."[1]

1. **Bergh A A & Dean P J.** *Light-emitting diodes.* Oxford: Clarendon Press, 1976. 591 p. (Cited 90 times.)

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