

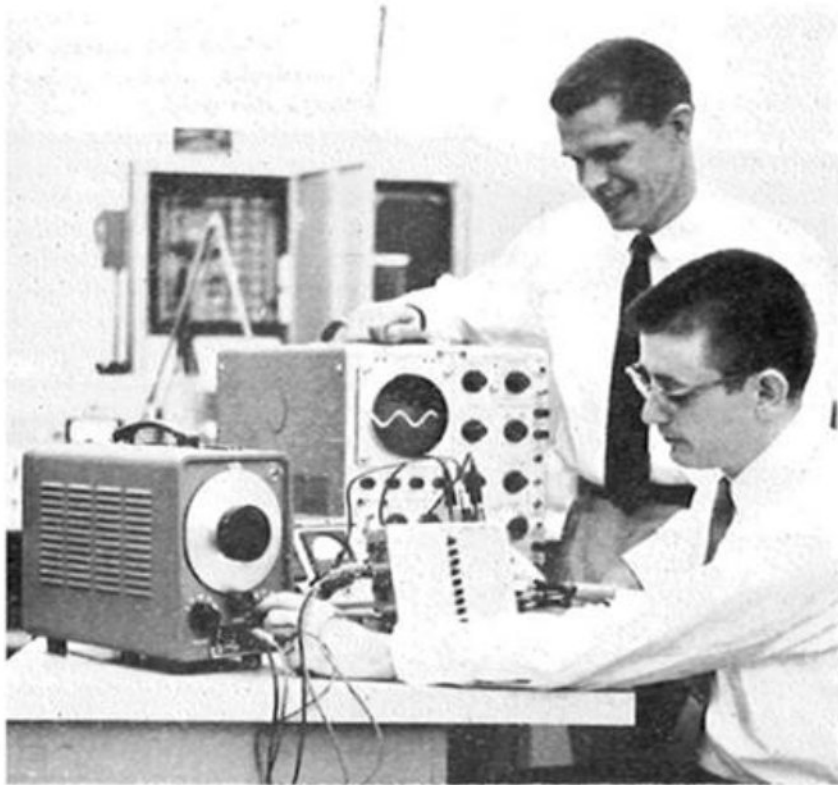
The First Practical LED

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The invention of the light-emitting diode marked the formation of the multi-billion dollar optical communications industry. Its discovery transformed the electronics world and our daily lives. Unlike ordinary incandescent light bulbs, LEDs emit light solely due to the movement of electrons in a semiconductor material. LEDs do not have a filament that will burn out, which makes them more efficient, durable, versatile, and longer lasting than the average light bulb. A common misperception is that the first practical LED was red. It was in fact near-infrared.

The story begins in 1959 at Texas Instruments (TI) in Dallas, TX when the company received a contract with the U.S. Air Force to build low noise parametric amplifiers for use in X-band (10 GHz) radar receivers. The high electron mobility of the semiconductor material gallium arsenide (GaAs) made it the material of choice for high-frequency varactor diodes. An employee named James R. "Bob" Biard had been working on the design of low-frequency (10 Hz) reactance amplifiers for use in long period seismometers since his hire date on June 3rd, 1957. Bob was hired, along with his former professor Walter T. "Walt" Matzen, three days after receiving his PhD in Electrical Engineering from Texas A&M University.



Walt (top) and Bob (bottom) demonstrate a low-drift d-c differential amplifier in 1958. Output of the amplifier is visible on the oscilloscope screen.¹

Bob's co-worker Gary E. Pittman, a graduate of Southern Methodist University, had been working with GaAs to create solar cells since 1958. Due to the experience they gained working on these projects, Bob and Gary were teamed up in the Semiconductor Components Division of the Semiconductor Research and Development Laboratory (SRDL) with the task of creating GaAs varactor diodes for use in reactance amplifiers for X-band (10 GHz) radar receivers.

The GaAs varactors they made were created by diffusing zinc into N-type bulk crystals of GaAs. An electroless plated nickel contact was applied to the N-type surface and a zinc/gold contact was applied to the P-type surface. The electroless nickel plating solution only worked because it had a lot of sulfur impurity. They previously tried evaporating pure nickel, however, they didn't get any Ohmic contact. They put a gold ball bond on top of the device, pulled the lead off, and then used that as a mask for etching a mesa on the varactor diodes. Gary etched the mesa by hand using a mixture of aqua regia and HF.

In late June of 1959, their boss Bob Pritchard came back from the Solid-State Device Research Conference (DRC) with a report about the Esaki tunnel diode. After hearing this report, Gary dug down into his 500 ml beaker of reject varactors and found 4-5 Esaki diodes. Bob and Gary had been building Esaki diodes by accident and discarding them as rejects. They made the Esaki tunnel diodes by alloying tin (Sn) dots into degenerate P-type GaAs. The tin donor concentration in the alloy regrowth region was quite high (approx. $1 \times 10^{20} \text{ cm}^{-3}$). A 2-to-1 change in the P doping of the material they were alloying the tin dots into would change the peak current density by 5 orders of magnitude. These devices had to be electrolytically hand etched in order to control the peak current density. It was necessary to change the area to make the devices come out with the same peak current.

Some of these tunnel diodes had a poor peak-to-valley ratio. The valley current was very noisy with a lot of 1/f noise. Bob came up with a flawed theory to describe this chaotic current as a radiative recombination generation in which an emitted photon was stimulating other centers to discharge. Based on this flawed model, Bob thought it might be possible to use the stimulated emission to make a GaAs laser diode. He took this idea to the Physics research lab across the street at TI. The CRL personnel showed him a paper written in 1954 by William Shockley and W. Van Roosbroeck² and tried to convince him based on data taken on silicon that band-to-band recombination in semiconductors was not very probable, so you likely wouldn't be able to make a diode laser. Bob knew GaAs had a direct band gap because they were building tunnel diodes, however, neither him, nor Gary, nor anybody in the Physics lab at time knew that this would affect the radiative recombination in the material.

As a result of the flawed model and flawed advice, the laser diode was not pursued; however, an experiment was performed to test the model. Bob and Gary constructed a p/n junction tunnel diode on a zinc diffused area of GaAs semi-insulating substrate. After placing a gold-zinc metal layer onto P-type (P+) GaAs, they heated the P+ GaAs to a temperature at which the zinc diffused from the gold-zinc metal deposit into the P+ GaAs to form Ohmic contacts. They then etched away the zinc diffused P+ layer on most of the GaAs semi-insulating substrate except on

three of the corners. On two of those three corners, the zinc diffusion served as the Ohmic contact to the semi-insulating substrate.

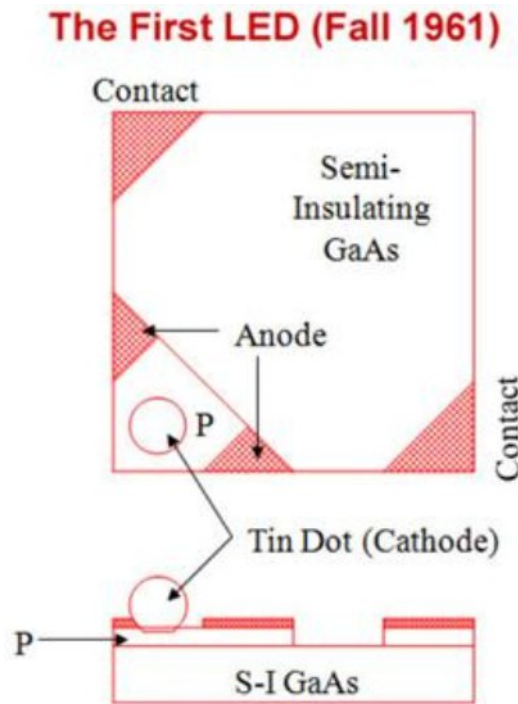


Fig. 1: Diagram of the tunnel diode constructed on a zinc diffused area of gallium arsenide semi-insulating substrate.

On the third corner, the gold-zinc formed the anode Ohmic contact of a tunnel diode, which was formed by alloying a tin dot into the zinc diffused layer. The tin dot also served as the cathode Ohmic contact. When the tin dot melted on the surface of the heavily doped P+ GaAs, it dissolved some of the GaAs into the liquid dot. When it cooled, the GaAs grew back out onto the P-type GaAs as a single crystal deposit. The regrowth layer under the cooled tin dot became heavily doped N-type (N+) because of the high concentration of tin, which acts as a donor impurity. The regrowth layer sitting on the P-type GaAs layer formed the N+P+ GaAs junction, which makes the tunnel diode. On the third corner, they also left enough P+ material to form the anode contacts to the tunnel diode on top of the chip. The Ohmic contact to the N+ regrowth layer was a tunneling Schottky diode between the tin metal in the dot and the N+ regrowth layer. The Ohmic contact to the P+ GaAs was a tunneling Schottky diode formed between the P+ zinc diffused layer and the gold layer.

During their experiment, they monitored the change in resistance between the two side Ohmic contacts on the semi-insulating substrate by connecting an external resistor in series with the two side contacts. The series combination was biased between a power supply (1.5V or higher) and a ground. They measured the change in voltage to the ground at the point where the series resistor connected to one of the side contacts. When they biased the tunnel diode into the valley current region, nothing happened; however, when they biased the diode into the forward conduction region,

they discovered a significant drop in resistance between the two side contacts. As the resistance dropped, the voltage between the two side contacts also reduced. This photoconductive response in the semi-insulating material was a result of absorbing photons emitted from the forward biased tunnel junction. The photons were infrared, which cannot be seen by the human eye, so at the time they didn't know if it was an optical effect or carrier injection; however, they did know it was some type of action at a distance. It wasn't actually necessary for the junction to be a tunnel diode in order to observe the photoconductive effect. They picked that structure because it was easier to fabricate. They would have gotten the same result, if they had deposited an N-type layer on the semi-insulating substrate and diffused zinc into it to form the p/n junction.

In Sept. of 1961, a Japanese firm brought an infrared (IR) image converter microscope to TI for evaluation by the Quality Control Department. TI planned to use the microscope to inspect silicon wafers. The IR microscope allowed you to look through the wafers in order to check for inclusions or defects. When Gary and Bob heard about the microscope being in the plant, they took some varactor diodes, tunnel diodes, D cells, and clip leads to the Quality Control Department. They forward biased the diodes and then examined them under the microscope. They found that both the tunnel diodes and varactor diodes glowed under forward bias. The light was being emitted from the junctions in the near infrared, around 9,000 Angstroms (~900 nm wavelength).

On the tunnel diodes, the light could be seen at the edges of the chip. At the 900 nm wavelength, the semi-insulating GaAs substrate of the device in Figure 1 is a photoconductor, so it responded to the light emitted by the N+P+ junction. When the device was forward biased, minority carrier electrons were injected across the junction. Since the N-type layer was more heavily doped than the P-type layer, the major carrier injection was minority carrier electrons into the P+ material immediately under the tin dot alloy region. Very few holes were injected into the N+ regrowth region under the tin dot. The injected minority carrier electrons recombined with the majority carrier holes in the P-type material resulting in the emission of infrared photons with energy close to the band gap of GaAs. Because the GaAs was so heavily doped, the band gap decreased and some of the recombination occurred in the band tails produced by the doping impurity that was added when the P-type layer was diffused into the semi-insulating substrate.

The varactor diodes that emitted light were P++N- diodes with an etched mesa geometry. The IR light came out around the edge of the mesa. The varactor diodes were made by diffusing zinc into lightly doped N-type (N-) GaAs. The zinc diffused layer was P+ and covered the entire wafer. In order to control the area of the varactor diode, a mesa had to be etched through the P+ diffused layer and slightly into the N- GaAs. Forward biasing the varactor diodes caused minority carrier holes to be injected into the lighter doped N-type GaAs. Photons were emitted when the minority carrier holes recombined with the majority carrier electrons in the lightly doped N-type material. The varactor diodes had a reasonable breakdown voltage (10-15V) and did not show the negative resistance characteristic of the tunnel diode. Later, when fabricating varactors, they went to a patterned P+ diffusion by depositing an oxide on the surface of the N- GaAs, so that the zinc only

diffused in where they etched away the oxide. In that case, the mesa etch was not necessary because the area of the varactor junction would be determined by the opening of the oxide layer.

The observation that light was emitted from both the tunnel diode and the varactor diode proved that it was a minority carrier recombination effect in the direct band gap semiconductor GaAs. They suspected all of the solar cells that Gary had been building years earlier had been LEDs, however, they never did go back to check them. At first, their diodes were not accepted by the Central Research group at TI because they were convinced the diodes did not emit useful amounts of light. That led Bob and Gary to create a zinc diffused p-n junction GaAs LED with spaced cathode contacts on the N-type face of the wafer to allow for fast, high-efficiency emission of infrared light from most of the top surface of the chip. By Oct. of 1961, they had demonstrated efficient light emission and signal coupling between the LED and an electrically-isolated silicon photodetector.³ At the time they thought they were the only people who knew about GaAs light emission. They had declared it a trade secret. However, at the Solid-State Device Research Conference in July of 1962, the first 5 papers on the program were on LEDs.⁴ TI had a man on the paper selection committee and he didn't tell them to submit a paper, so they didn't get a publication at the conference. However, they did get the patent after the DRC had blown their cover that GaAs emits light.

On Aug. 8th, 1962, Bob and Gary filed a patent application based on their findings titled "Semiconductor Radiant Diode". After establishing the priority of their work, the U.S. patent office issued the two inventors the patent for the GaAs infrared (IR) light-emitting diode (U.S. patent 3,293,513).⁵ This was the first U.S. patent for a practical light-emitting diode. It took four years for the patent to issue because it was in interference with patents submitted by many of the other U.S. research labs including GE Labs, RCA Research Labs, IBM Research Labs, Bell Labs, and Lincoln Labs at MIT. It was determined based on dated entries in their engineering notebooks that Bob and Gary had a 3-6 month priority over all the other research labs. Since that time, the U.S. patent office has used filing date to establish priority rather than notebook entries. Bob and Gary's patent used gallium arsenide (GaAs), a III/V semiconductor, while most other organized research seeking LEDs at the time used II-VI semiconductors like cadmium sulfide (CdS) and cadmium telluride (CdTe). The problem with the II-VI material is that it usually comes in either N-type or P-type, not both, which makes it very difficult to make p-n junctions. TI gave Bob and Gary \$1.00 each for their patent.

Their patent was preceded by U.S. patent 3,102,201, which was filed on Dec. 15th, 1958 by Rubin Braunstein and Egon Loebner of the Radio Corporation of America (RCA).⁶ The RCA patent qualifies as a germanium LED, however, the light emitted had a very long wavelength (~1.4 microns) and a very low optical modulation bandwidth. To detect light at that wavelength with a germanium photodiode with good efficiency would require operating the photodiode at a higher temperature than the LED. Increasing the temperature of the photodiode reduces the band gap and increases its responsivity. It would also increase the photodiode's leakage current, which would have a negative impact on the signal-to-noise ratio. The easiest way to modulate the light output of

any LED is to modulate the bias current. The RCA patent describes modulating the light output by changing the surface recombination with bias on a transparent electrode.

Immediately after filing the patent, TI began a project to manufacture infrared diodes. In Oct. of 1962, they announced the first commercial LED product, the SNX-100 GaAs LED. It sold for \$130 per unit. TI advertised the SNX-100 as available for "experimental engineering evaluation".⁷ It came in a TO18 (or TO46) transistor header and employed a pure, 50 x 50 mil⁸ GaAs crystal to emit a near-infrared 890-m μ light output. For light-emitting devices, the top of the TO18 case had a transparent window, lens, or parabolic reflector rather than a sealed, flat top. A typical output of the SNX-100 was 2 x 10¹⁴ photons/sec, when driven by a 100 mA current source. The SNX-100 used gold-zinc for the P-type contact and tin alloy for the N-type contact. Gary achieved the N-type contact by plating molybdenum wires with tin and alloying them into the N-type surface of the die using a strip heater. It made an excellent N-type contact, but was in no way a production process by today's standards.

On Oct. 25th, 1962 at the International Electron Devices Meeting in Washington, D.C., Bob and Gary published an article titled "GaAs Infrared Source" to discuss their new device.⁹ On May 21st, 1963 at a Components show in Olympia, London, TI put on display a communications link which used the SNX-100 in combination with a binary-to-decimal decoding matrix, a transistorized closed-circuit television network, and a television tuner using a germanium mesa transistor.¹⁰

In Oct. of 1963, TI announced the first commercial hemispherical LED, the SNX-110. This device employed a 72 mil⁸ dome shaped exit surface (Fig. 2, bottom) to eliminate total internal reflection and provide quantum efficiencies of ~ 2.5% at room temperature and ~ 15% at liquid nitrogen temperatures. These devices supplied a continuous optical output power of 1.0 watt at 78° Kelvin. Gary and William N. Carr published a paper on Nov. 15th, 1963 in the *Applied Physics Letters*, which described the 1.0 watt GaAs source.¹¹ In Feb. of 1964, Gary and William N. Carr published another paper about the device in the *Proceedings of the IEEE* titled "Quantum efficiency of a new GaAs spontaneous infrared source". The light being emitted from the GaAs source was collected by an array of two Texas Instruments type 29200 silicon solar cells. The solar cells were spaced 0.5 cm from the GaAs source and mounted on a copper heat sink maintained at room temperature.¹²

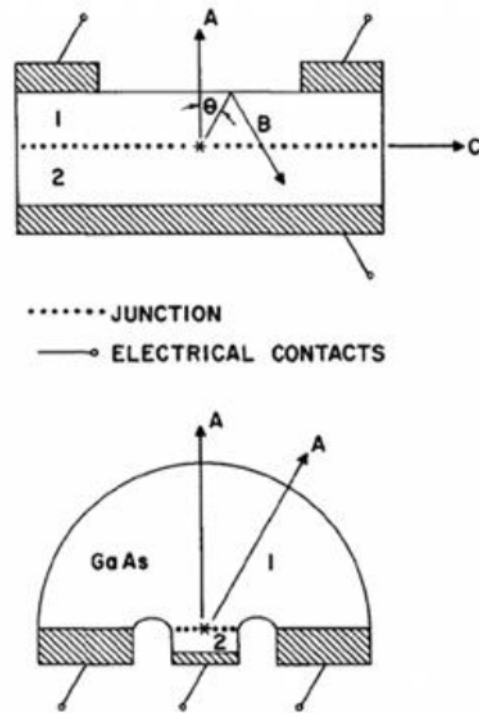


Fig. 2: Top - optical paths in a rectangular source; Bottom - optical paths in a hemispherical source.¹¹

In the mid-1960s, Bob was placed in charge of both the Optoelectronic branch and the MOS branch in the SRD Lab. In 1964, TI's Opto branch developed a monolithic visible LED element consisting of a 3x5 array of red LEDs capable of displaying the numbers 0-9. The device was lacking a means of driving the array, so Dr. Biard and Bob Crawford (from the MOS branch) designed a P-channel MOS circuit using binary coded decimal inputs to turn on the appropriate 15 output lines. The MOS circuit worked on the first pass and was implemented into a simulated cockpit altimeter. In March of that year, TI displayed the altimeter in a booth at the New York IEEE show and convention. At this convention, TI also demonstrated a hearing aid, which was the first consumer product using TI's integrated circuit. The CMOS circuit that Dr. Biard and Bob Crawford designed resulted in the patent for the MOS Read Only Memory (U.S. patent 3,541,543).¹³ This was the first time a Read Only Memory had been made using MOS transistors.

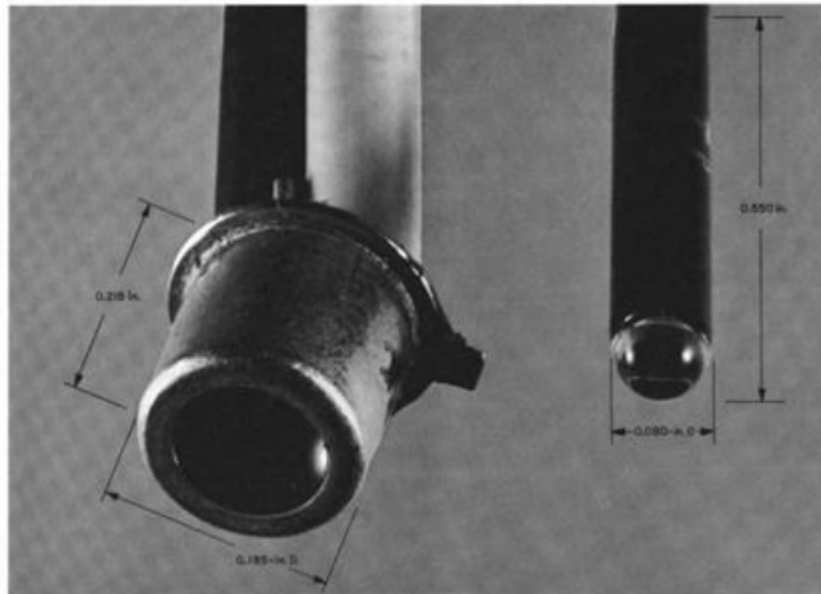


Fig. 3: An SNX-100 GaAs LED (left) contained in a TO-18 transistor metal case next to an LS-400 planar silicon photosensor (right).¹⁵

In Sept. of 1964, researchers affiliated with the JPL space program investigated the potential use of a film scanner system, which used the SNX-100 LED as a light source and an LS-400 silicon planar photosensor as the light sensor (Fig. 3). A camera-film processor, which had been designed for spacecraft-borne systems to take planetary photographs, required the film scanner system to convert the film density to electrical signals for data transmission. The SNX-100 was ideal because it was small and did not require high voltage like photomultiplier tubes.¹⁴ It could be operated at low voltages (1.5 V) with its light output modulated at extremely high frequencies by simply modulating the diode driver current. The light output had a narrow band of 50 m μ and was used to illuminate a circular aperture, which was reduced by optics to the required diameter at the film plane. The LS-400 signal sensor used was a high-beta, low-signal-level transistor with its TO 5 can removed.¹⁵ Its base lead permitted direct current biasing of the base-emitter circuit. The actual

breadboard scanner system maintained a rigid alignment between the light source and the light sensor.¹⁶

The infrared LEDs were initially a bit steep in price to find widespread application, but they did begin to open up the field of optoelectronics. TI had already entered the optoelectronic component market with a phototransistor, which came in a small package called the Pill Pack, used in the IBM 059 Card Verifier (Fig. 4). The IBM 059 Card Verifier was the companion to the IBM 029 Card Punch (announced Oct. 14th, 1964). The phototransistor detector was used to read holes in punched cards that were used to input data into computers. The light source was a tungsten ribbon lamp made by GE with a fiber bundle to distribute light to the 12 rows of holes on the card. The Verifier previously used wires to read the punch cards by reaching through the holes and making electrical contact to a metal plate below the card, which tended to damage the punch cards.

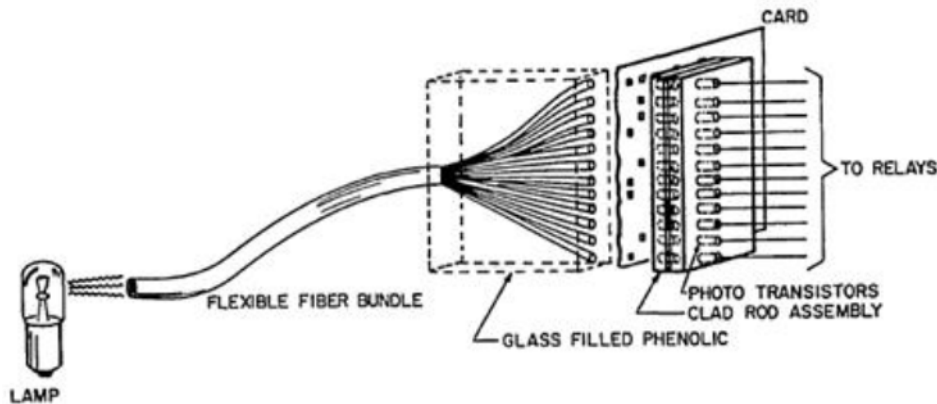


Fig. 4: Optical system of IBM 59 Card Verifier.¹⁷

TI put an array of 12 infrared liquid epi LEDs in the Pill Pack with a printed circuit board on one side of the punch card and a PC board with the 12 Pill Pack photodetectors on the other side of the punch card. The setup completely replaced the incandescent lamp and fiber bundle assembly. The infrared light was sent through the holes or blocked by the card, which not only significantly reduced the size and power required, but also improved the reliability compared to the incandescent lamp. The liquid epi LEDs were second generation devices that came along pretty shortly after the SNX-100. TI and other companies had made large investment in material growth and purification. There were rudimentary techniques for Ohmic contact and diffusion, however, the technology was ready to support the development of the LED.

In June of 1965, TI introduced the miniature TIXL01 GaAs light emitter. It was a tiny 1/10" high planar LED with a 1/16" diameter. One hundred TIXL01 LEDs could be mounted in every square inch of a 1/16" thick printed circuit board to simplify circuit assembly.¹⁸ By Nov. of 1965, TI had also released other GaAs LEDs including the medium-powered TIXL02, the TIXL03, and the PEX1004 (Fig. 5). The TIXL02 (an improved version of the SNX-100) had an etched flat geometry. The TIXL03 (an improved version of the SNX-110) was of planar construction and came in a hermetically sealed package with a flat glass window in the top of the case. The emitting surface was hemispherical with a 0.07 in. diameter. The light output was 15 mW at .92 microns with an excitation of 2 amps at 1.5 volts.¹⁹ The PEX1004 had a planar construction and used a flat lens to project a 120° beam through the package's aperture.²⁰

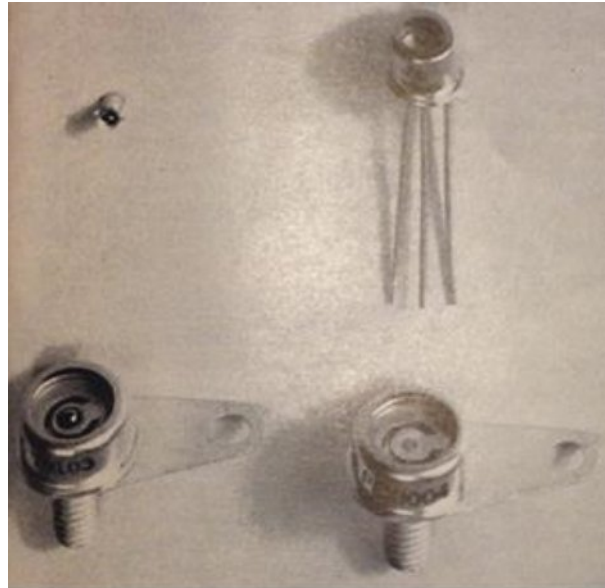


Fig. 5: Typical gallium-arsenide light sources. The TIXL01 (top left) permits high mounting densities. The TIXL02 (top right) comes in a package similar to the Jeduc TO-18 case. The two bottom units: TIXL03 (left) and PEX1004 (right).¹⁸

In Aug. of 1966, TI released a solid-state opto-electronic isolator device known as the TIXL101 (Fig. 6). It combined an LS600 planar silicon light sensor with the TIXL01 in a single, opaque, cylindrical, epoxy package (0.22 in. x 0.35 in.).²¹ The TIXL101 was particularly suitable for eliminating some of the difficulties encountered when using electromechanical switching devices in systems (e.g. telecommunications relay lines). The TIXL101 permitted high voltage electrical isolation (up to 5,000 V) and offered faster switching times, a smaller size, and a more reasonable cost to drive simple amplifier circuits.²²

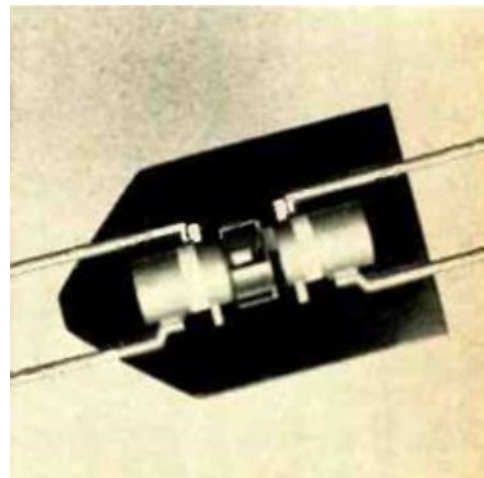


Fig. 6: TIXL101 optoelectronic isolator²²

Before introducing the infrared LEDs to the market place, they did extensive reliability testing. They found that the reliability problem in the tunnel diodes also affected the LED. When you biased the LED in the forward direction at a constant current, the light output of the LED went down with time. This degradation in quantum efficiency was characterized by localized non-radiative lines of very low lifetime in the diffused P-type layer. These dark line defects were formed by recombination centers which contributed additional nonradiative current. When the LED was biased at a constant current, the growth of the dark line defects over time caused an increase in the

nonradiative current, which resulted in a decrease in the amount of current used to emit light. Time-lapse photographs of the degradation (Fig. 7) showed that these dark lines originated at the perimeter of the junction and then propagated toward the interior of the junction (the emitting area of the diode) along specific crystallographic planes.

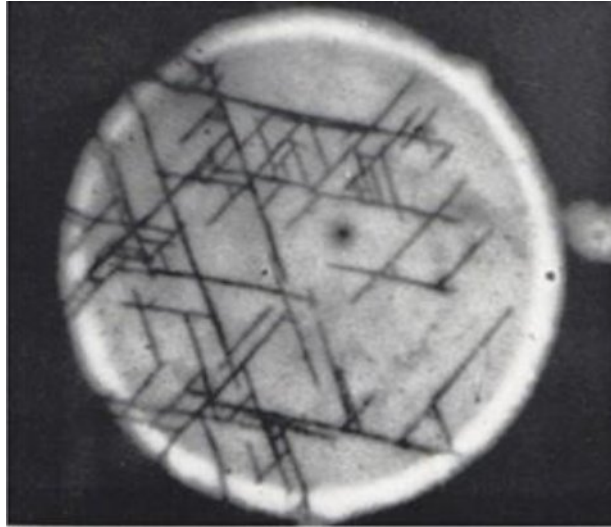


Fig. 7: Infrared photograph showing dark lines associated with degradation.²³

The dark lines behave like extensions of the diode perimeter and result in an increase in depletion layer recombination, which gives rise to "2kT" non-radiative current. The degradation did not change the material between the dark lines, however, it does cause the diode to become more conductive and the light output to go down, when using a constant current bias. No degradation was observed for reverse bias, shelf storage at elevated temperature, or low current-density forward bias. In Sept. of 1966, Bob, Gary, and J.F. Leezer published their findings at a Gallium Arsenide Conference in Reading, England.²³ The dark line defects were re-discovered at Bell Labs in 1973.²⁴ Fortunately, one of the reviewers of the Bell paper remembered their earlier publication and saw to it that their paper was referenced.

In Nov. of 1967, TI's GaAs devices were available for \$20 a unit. By that point in time, the LED had achieved nearly 100% internal quantum efficiency whereby each injected carrier emits one photon.²⁵ In May of 1969, Bob left TI to join Spectronics Inc. as Vice President of Research, when the company was founded. Gary served as Vice President of manufacturing. While at Spectronics, Bob worked on the design and development of silicon photodiodes, phototransistors, photodarlington devices, and GaAs light-emitting diodes. He also designed and developed most of the special test equipment used at Spectronics for component calibration and evaluation such as a spot scan microscope, a radiation pattern plotter, and constant temperature burn-in racks for LEDs. In 1974, Bob worked on the development of optical couplers used in a data bus developed for airborne avionics systems. In Nov. of 1978, Tom M. Hyltin, a former engineering manager at TI, published a book titled *The Digital Electronic Watch*, in which he cited Bob and Gary's 1961 discovery as being fundamentally important to the creation of the digital wrist-watch.²⁶

In 1978, Spectronics was acquired by Honeywell. From 1978 to 1987, Gary and Bob worked at the Honeywell Optoelectronics Division in Richardson, TX. Bob worked as Chief Scientist, while Gary served as director of military business. Bob started their MICROSWITCH IC & Sensor Design Center and served as a member of the Components Group Sensor Planning Team. He was also the Components Group representative on the Honeywell Technology Board (HTB), which was concerned with the development and transfer of technology throughout the Honeywell corporate structure. Bob's product development responsibilities included optoelectronic components (light emitting diodes and photodetectors), fiber optic components, transmitter & receiver modules, silicon Hall effect sensors, and pressure sensors.

In 1987, Bob became Chief Scientist of the Honeywell MICRO SWITCH Division. He held this position until he retired in Dec. 1998, only to be hired back on as a consultant. As a consultant, he became part of a team developing Vertical Cavity Surface Emitting Lasers (VCSELs). He was also involved in the interface between the MICRO SWITCH division, the Honeywell Corporate R&D Laboratory, and universities. In 2006, Honeywell sold the VCSEL group to the Finisar Corporation, which hired Bob on half time as a consultant Senior Scientist for the Advanced Optical Components Division in Allen, TX. While working for Finisar, Bob has been issued a total of 30 engineering patents related to the design of 850 nm VCSELs and photodiodes used for high-speed fiber optic data transmission.



In loving memory of Gary E. Pittman (1930 - 2013).

In Nov. of 2008, Gary received the Lazenby Outstanding Alumnus Award from the SMU Chemistry Department. That is the highest award SMU can bestow upon its former students. The

award was given in recognition of co-inventing the GaAs LED and his ongoing research on residential energy reduction and the improved use of medical statistics.

In May of 2013, SMU awarded Bob the degree of Doctor of Science, honoris causa, for the LED patent. Three months later, during a recollection of the patent, Bob stated the following:

"The first diodes that we saw emitting light were not designed to be LEDs. They were varactor diodes and tunnel diodes, which had the entire N-type surface and P-type surface covered with Ohmic contact to achieve a low series resistance. They did not emit very much light, but it was enough for us to see with the IR image converter microscope. That led us to create a structure in which the N-type surface of the chip had spaced contacts, so the light emitted at the junction could be emitted from most of the top surface of the chip. With a rectangular chip of GaAs, most of the light emitted at the junction was reflected at the exit surface. The index of refraction of GaAs is 3.6 and air has an index of 1.0. This means that ~97% of the light emitted at the junction is totally internally reflected at the exit surface. The highest quantum efficiency that can be expected from a rectangular LED chip is ~2%, even with an anti-reflection coating on the optical exit surface. This total internal reflection problem led us to come up with the hemispherical dome LED. In this diode the N-type GaAs substrate is shaped into a hemisphere and the hemispherical surface is covered with an anti-reflection coating (preferably silicon nitride) to minimize front surface reflection. The LED p-n junction is in the center of the flat face of the hemisphere. The central P-type region is covered with the anode Ohmic contact. The cathode Ohmic contact was a donut shape that covered most of the remainder of the N-type flat surface of the hemisphere. By making the diameter of the hemisphere 3.6 times larger than the diameter of the P-type layer, all the light at the exit surface of the hemisphere was inside the critical angle for total internal reflection. This resulted in a huge increase in quantum efficiency because up to 50% of the light emitted at the junction could escape from the chip at the hemispherical exit surface. The other half of the light went toward the P-type Ohmic contact and was absorbed in the GaAs. The absorption in the thicker N-type GaAs between the junction and exit surface resulted in less improvement in quantum efficiency than what we had hoped for, however, the dome LEDs were much more efficient."

As Bob will tell you, the LED happened out of the overflow. It was not a result of a project to come up with that idea. They weren't even thinking about LEDs. It was a result of being in the right place at the right time. They were building LEDs for several years and didn't know it. They used the infrared microscope and saw all of the GaAs p-n junctions were glowing and were able to capitalize on it.

Today LEDs are typically made of the semiconductor material aluminum-gallium-arsenide (AlGaAs). The fiber optic cables that make our wired world possible rely on infrared light emitted by descendants of Bob and Gary's infrared LED. Infrared LEDs also continue to be used in the remote control units of many commercial products including televisions, DVD players, and other domestic appliances.

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