INVITED PAPER

The III–V Alloy p–n Diode Laser and LED Ultimate Lamp

The issue begins with a historical perspective on the III–V alloy diode laser and describes why the LED is an "ultimate lamp."

By Nick Holonyak, Jr., *Life Fellow IEEE*

ABSTRACT | In this paper, an account is presented of the semiconductor, because of the energy gap bipolar with electron (e) and hole (h) conductivity, becoming ingeniously with little or no technology (Bardeen and Brattain, Dec. 1947) the transistor, a triode (at first just a germanium "base" crystal and a point contact "emitter" and "collector"), a low impedance "emitter" minority carrier input (I_E) into a (the) vital central "base" active region, the base supporting along with essential recombination current I_B ($I_B > 0$) carrier transport to a higher impedance "collector" output I_C ($I_E + I_B + I_C = 0$, $I_C/I_E = \alpha \sim 0.9$), hence gain, thus revealing at last that a current (I_B) can increase the electron–hole (e–h) population, and as a further consequence, yield band-to-band ($k_e = k_h$) excess carrier recombination radiation (light). The transistor established (1947) a basis for the study of the light-emitting diode (LED). The path to an "ultimate lamp," the p–n diode laser and LED, is described from semiconductor, to energy gap, e–h bipolarity, transistor, the p–n transition, excess carriers, e–h recombination, direct gap ($k_e = k_h$) crystal, autocatalytic e–h/photon interaction, spectral narrowing, stimulated recombination (laser), need for resonator (cavity Q, how?), direct-gap ($k_e = k_h$) III–V alloy, visible spectrum III–V alloy, III–V alloy gap change (ΔE_g), quantum-well (QW) e–h recombination, stimulated emission solving the problem of photon extraction ($\rightarrow$ 100% quantum efficiency), the p–n diode "ultimate lamp," return to the 1947 triode, to the transistor, and the base importance informing the realization of a QW-base transistor laser.

KEYWORDS | Light-emitting diode (LED); p–n junction and transistor; semiconductor laser

I. INTRODUCTION (SEMICONDUCTOR, BANDGAP, ELECTRONS, AND HOLES)

By now a significant fraction of Earth's billions of people has seen a light-emitting diode (LED), but with no doubt still an appreciable number is not aware it is not a conventional light source, not a wasteful hot filament, instead an electronic source related to the transistor, in fact, a product of the transistor world. In my view, the history of the LED, the LED we know today, does not begin, as some maintain, in the early part of the 20th century with essentially accidental experiments giving mysterious current-induced light emission from primitive crystalline material, for example, poor quality SiC. In the early activity, there is no basic understanding and continuity of effort, no direct path leading to the p–n LED, to an "ultimate lamp," just occasional hit and miss experiments (guessing) from ~1900 until after the arrival of the transistor. The real journey, a direct path to the LED and closely related diode laser, does not begin until the advent of quantum physics, until the analysis and idea that a semiconductor has an energy gap, a forbidden gap in electron energy (E_g), and that a photon or heat can excite an electron across the gap from the valence band (E_v), from the atomic bond structure of the crystal, to the higher energy conduction band (E_c), where the electron (negative, n) is free to move and conduct. Similarly, the "hole" (positive, p) left in the valence band, the void (+) itself, the charge unbalance left by the missing electron, is free to shift in position, free to move and conduct in the crystal structure, all owing to the energy gap $E_g = E_c - E_v$. In the crystal, the hole is as real as the electron. A nonequilibrium electron and hole (e–h), say, generated by a photon (or current?), can recombine across the energy gap (E_g) returning (yielding)

Manuscript received December 3, 2012; accepted May 3, 2013. Date of publication August 22, 2013; date of current version September 16, 2013.
The author is with the Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801-2918 USA (e-mail: nholonya@illinois.edu).

Digital Object Identifier: 10.1109/JPROC.2013.2274909

a photon ($\hbar\omega \sim E_g$). The gap is fundamental. It defines the semiconductor and is "everything." It is a gift.

II. TRANSISTOR ELECTRON AND HOLE (e–h, −/+) CURRENT

In the semiconductor, the hole is real, in fact, so real that "no hole, no transistor," nor later LED or diode laser, and now even a transistor laser. The transistor, so important, using equally plus and minus (+/−) charge, bipolar fundamentally in conductivity and operation, gave identity to the previously obscure hole. The electron and hole are "tied" together across the bandgap by a photon ($h\nu = \hbar\omega \sim E_g$, light), either in absorption or in e–h recombination yielding light or in the case of defects heat. In the proper choice of semiconductor, in a so-called direct-gap crystal ($k_e = k_h$ or $k_n = k_p$, as in the $E - k$ diagrams of Fig. 1, with no offset $[k_e - k_h = \Delta k = 0]$ in conduction band electron wavevector (momentum) and valence band hole wavevector), e–h recombination (the base current I_B in a transistor) means as a consequence light, electronics light, lots of light, as much as 100% quantum efficiency ($h\nu = \hbar\omega$, Fig. 1). We see already where this is going: current-in and light-out, a LED (also a laser, a high level special form of LED); light-in and current-out, a solar cell. Conceptually, this all comes out of quantum physics and wave-particle equivalence, the source of the $E_n - k$ and $E_p - k$ diagrams of Fig. 1 (e–h particle-wave dispersion relations separated in energy $\Delta E \sim E_g$ vertically but in k-space aligned horizontally with no k shift, $k_e = k_h$, $\Delta k = 0$) governing the quantum particle (e or h) wave, with all of this serving as the basis for the transistor, Bardeen and Brattain's remarkable 1947 invention [1], [20] and a new word in the language. The transistor made the hole, at first a quantum construct, real, tangible, useful, a mobile positive (+) twin entity equivalent to the electron (−). The transistor, bipolar (+ and −) and focusing attention on the electron and hole, the gift of the gap, gave identity to the hole and more visibility to the semiconductor. It gave importance to the semiconductor and its study. In fact, we may ask, transistor or semiconductor, which is "chicken" and which is "egg"? Did the device "make" the material or the material the device?

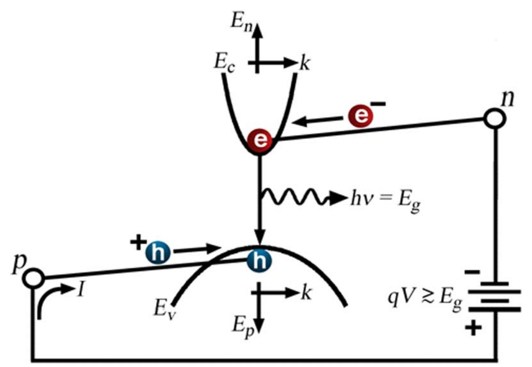

Fig. 1. ***Skeletal flat-band hybrid diagram, spatial and E–k (crystal quantum particle dispersion relation, $k = 2\pi/\lambda$), of a p–n (left to right) LED "ultimate lamp." Just the relevant doped conducting band edges are shown cross connected top-to-bottom e-to-h (n-to-p) via the E–k diagram recombination active region E_n–k_n separated by $\Delta E = E_g$ from E_p–k_p (with $k_e = k_h$ or $k_n = k_p$).***

III. TRANSISTOR ELECTRON–HOLE BASE-CURRENT RECOMBINATION, SEMICONDUCTOR e–h LIGHT, p–n "ULTIMATE LAMP"

As I heard Bardeen explain many times, as his first student and then colleague for 40 years (1951–1991), it was not known until the transistor (December 1947) that a current could create a nonequilibrium e–h population in a semiconductor and, most important for our purposes, e–h recombination could reestablish equilibrium delivering photons (light), for example, as in Fig. 1. Current could "make" (generate) excess e–h pairs, thus recombination, thus light, thus Fig. 1. The transistor changed everything. It changed the world. In the simplest form, just the relevant band edges connected e-to-h (n-to-p) via the $E - k$ active region, Fig. 1 is (left to right) a p–n LED "ultimate lamp." Constructed with a resonant cavity (mirror edges and more cavity Q), it becomes a diode laser. Electron (e) current from the n-type right side (donor doped) is carried via the quantum-wave "mechanics" (the particle-wave dispersion relation) of the $E_n - k$ conduction band and hole current from the opposite p-type side (acceptor doped) via the hole particle-wave "mechanics" of the $E_p - k$ valence band, giving at the p–n transition, at the E_g bandgap e–h plus–minus crossover ($E_c \rightarrow E_v$) in conduction, e–h injection and recombination radiation (light). The skeletal schematic diagram of Fig. 1 is almost the whole LED "story," "proof without words" of a p–n "ultimate lamp," nothing wasted in converting electrical to optical energy (light), a device with current conduction from end-to-end carried by e–h recombination, an energy-loss ($\Delta E \sim E_g \sim \hbar\omega$) +/− switch in charge polarity across a direct ($k_e = k_h$) energy gap E_g [now generally modified with a quantum well (QW)].

After the transistor, current-generated light emission from a semiconductor could at last be explained and exploited, a gift of the bandgap. As we study recombination for transistor reasons (for electronics), we are on the path also to the laser and LED, especially as we go from the more limited indirect-gap ($k_e \neq k_h$, $k_e - k_h = \Delta k \gg k_{\text{photon}}$) elemental transistor materials germanium and silicon to the III–V compounds, to the direct-gap ($k_e = k_h$, $\Delta k \sim 0$, Fig. 1) GaAs class of materials and their stronger band-to-band e–h coupling (photon coupling, $k_{\text{photon}} \sim$ small, $k_e - k_h = \Delta k \sim k_{\text{photon}}$, thus conserving wavevector $[k]$ or momentum, $p = \hbar\, k$, $\hbar = h/2\pi$, $k = 2\pi/\lambda$, $h =$ Planck's constant). It is the transistor and the study of e–h recombination in the transistor, the vital base current, that led to the diode laser and LED. The transistor changed electronics, indeed, created a new electronics (now colossal) that changed the world.

IV. DIRECT-BANDGAP ($k_e = k_h$) $GaAs_{1-x}P_x$ III–V ALLOY VISIBLE-SPECTRUM p–n ''ULTIMATE LAMP''

Studying GaAs for device reasons in 1960–1962, I was not satisfied with gallium arsenide's 1.4-eV energy gap (infrared photon wavelength, $\lambda \sim 0.9$ μm), and learned how to make and shift GaAs toward GaP, to the alloy $GaAs_{1-x}P_x$, toward, say, $E_g \sim 2.00$ eV ($x \leq 0.45$), toward visible-red wavelengths, but still a direct-gap crystal ($k_e = k_h$, Fig. 1) so that $k_e - k_h = \Delta k \sim k_{\text{photon}}$. When (1962) the small number of us, the ones not misled by discrete-state laser operation (a Maiman laser, 1960) [2], [21], realized that a simple GaAs p–n junction, not ideal but still a substantial incoherent signal source (an experiment and a guess, not a measurement, a supposition claiming high quantum efficiency but not verified) [3], [22], could serve (maybe?) as the basis of a laser (could it?), I wanted to work, not in the IR (infrared), but in the visible red where the eye sees. I knew (1960–1962) how to make the red-gap alloy $GaAs_{1-x}P_x$ [4], [23] and felt anything GaAs would do, I could do (and see!) with direct-gap $GaAs_{1-x}P_x$.

I knew from my grad-student days enough about oscillators and cavities, and the extension to lasers, to know I needed a cavity (a resonator) to help my "red" p–n junctions operate as lasers. Also, I did not want to compromise high-efficiency band-to-band (e→h, $E_c \rightarrow E_v$) recombination radiation with multistep contaminating deep impurity levels (not a good idea, a known source of loss, heat not light) in a vain attempt to copy the discrete transitions of previous lasers. From earlier studies of (e–h) double-injection negative resistance (Ge, Si, and GaAs p–"i"–n diodes) [5] I knew that I did not want to compromise high-efficiency band-to-band recombination with deep impurity levels (defects) and lossy steps in recombination. The semiconductor was different. It was a major mistake, nevertheless, a common, a widely held view, to assume that a semiconductor laser, presumably all lasers, required discrete (atom-like) transitions, a narrow spectral output, and that the broad band-to-band e–h recombination radiation spectrum of the semiconductor required something more, "discreteness" (why? how?), to function as a laser material. The poor assumption (wrong) of so many for the need of "discreteness," a narrow spectral line, overlooked the fact that the semiconductor, and its mobile e–h charge, generated band-to-band (e–h) recombination radiation in its own unique adjustable way. Electron, hole, and photon (connected) are autocatalytic in their operation across the bandgap and can adjust spatially and in energy to overcome the lack of e–h recombination discreteness. Operating autocatalytically, electron, hole, and photon (coupled) could "tune" spatially and in energy in recombination to accommodate spectral line narrowing. The semiconductor system does not start off with a narrow linewidth at low excitation level but, because of the electron–hole–photon, autocatalytic response, narrows at higher and higher excitation level.

I knew that the earlier spatially dilute discrete-transition laser work had little to teach us about the semiconductor, a large ($\sim 10^{22}$ atoms/cm^3) closely coupled atomic system (not dilute in form or atomically discrete in operation), nor about spontaneous and stimulated e–h recombination, or how to go from an incoherent (spontaneous) diode source to a coherent source, to a diode laser. The discrete-transition laser merely taught us that light could be coherent (but how in a semiconductor?), which indeed was reason enough to be grateful to Ted Maiman. What else did we need, maybe just the help of a cavity? Stimulated recombination, as such, in a semiconductor was known before the laser (see [6, pp. 200–202]). It had to be pursued further, at variable temperature and higher excitation level in a cavity at higher Q, not as in earlier work at low excitation level in lossy poorer geometry low Q samples or devices. It did not make sense to go from the band-to-band recombination radiation light generation of a diode, from a powerful efficient process to an unknown (an unjustified, a guessed) secondary weaker process (e.g., deep levels), maybe spectrally narrow but inevitably weaker and introducing more loss. It did not make sense to abandon a strong source in favor of a speculative weak source.

V. VISIBLE-SPECTRUM III–V ALLOY CRYSTAL (HOMEMADE OR ALIEN, WHOSE?)

I was sure, working in the visible red, that I would beat everyone to a diode laser, but my colleague at GE Schenectady, Bob Hall, also in the hunt for a laser (which we did not discuss at DRC, instead I argued with Bob Noyce about a GE-Fairchild p–n–p–n switch patent interference), was one step ahead of me and making his GaAs diodes with plane-parallel Fabry–Perot resonator edges, with the crystal itself the cavity (good idea, the simpler the better)! A more sophisticated external cavity, my initial thought at DRC, could come later (as happened), after first the simplest case, the crystal alone the cavity. It did not matter to me that GaAs could be bought, as is said, "off the shelf," and I had to make (requiring time, effort, and risk—both in competitive effort and threat of being fired for not working full time on Si) my own crystal, the more complicated higher gap alloy GaAsP. Some of my GE colleagues (Syracuse, NY, USA) considered me crazy and did not hesitate to tell me. They swore at me, good naturedly, and I at them in return. The coarse language of the streets of New York City did not exceed that of the immigrant coal miners of Southern Illinois, nor that of the unschooled railroad workers with whom I (lying about my age) dug-in railroad ties and repaired track as a teenager during World War II. Were III–V alloys viable or just a "lumpy" mess as some of my GE colleagues insisted? Where did I, not a chemist or a metallurgist, not a crystal grower, get the crazy notion I could make a high-gap III–V alloy? According to my GE Bldg 3 colleagues, "If you were a chemist, you would know you cannot do what you are doing". Weren't ordinary binary III–V's, say, GaAs itself, enough trouble, much more than elemental Ge or Si, not just to grow but to make into devices? "Why don't you just keep working on Si so that you don't get fired?" I understood and knew how to build semiconductor devices, but did I know how to grow crystals, not to mention a complicated III–V alloy not riddled with defects, and then make from it a diode laser, which itself was regarded as doubtful? In fact, had any high-gap III–V alloy ever yielded a "good" p–n junction device? Why increase the odds against success by working with a higher gap (> 1.4 eV) III–V alloy?

I still preferred the visible red over the infrared (IR). I wanted light I could see, that humans could see. I was convinced that the alloy GaAsP $= (GaAs)_{1-x}(GaP)_x$, $0 \leq x \leq 0.45$ (direct gap), although stochastic in As–P arrangement, but with the As and P atoms evenly distributed on proper III–V crystal lattice sites, was not "lumpy" and on average locally smooth enough structurally and in energy band properties to be a good p–n junction and viable light source, in fact, in my view could be a laser. After DRC I was sure I had a good chance to make a red semiconductor laser using a GaAsP diode light source aided, as are most oscillators, by a resonator (a cavity). I drew this conclusion based on my own GaAsP crystal growth and device work [4], [23]. I had reason, my own data, to consider GaAsP to be as good as GaAs, and I knew as well as others how to make III–V p–n junctions. I knew from my own work that As–P alloy disorder, random As–P occupation of column V crystal sites, was not a defect in the usual sense and that my GaAsP was "smooth" enough to give high-performance p–n junctions.

More than a decade ago, a Washington writer called me and asked, based on the writings and statements of a high-ranking former military officer, whether my red LED and laser GaAsP crystal, just as the transistor [7], came from the "little green men" of Roswell, NM, USA? Did it? What an insult to Bardeen and Brattain [1], [20]. I could not believe his question, the sheer effrontery. Can anyone believe such nonsense, or be so poorly educated (a writer?), or be that gullible? Why do the extraterrestrial "little green men" always emerge after the fact not before? How come they did not come and help when I might have needed help? In 40 years, Bardeen and I never talked, nor had a basis to talk, about the help of any "little green men" in what we knew or did, transistor or laser or LED. I did not insult him and he did not insult me with such nonsense. Returning home from an East Coast meeting, Bardeen did not stop in Syracuse on a Saturday late in 1962 to see my GaAsP lasers and see which "little green men" helped me. Incidentally, since the search for extraterrestrial intelligence (SETI) has so far for decades yielded no communication signals from space, why attach any importance to the SETI project if extraterrestrial "little green men" have already "hand-carried" so much information and various artifacts to Earth [8]?

VI. THE SEMICONDUCTOR LASER AND OSCILLATOR CAVITY (HOW?)

In an August 1962 Schenectady visit, dealing with a shared Air Force contract on III–V semiconductors, I told Hall I was working on a GaAsP laser and he told me he was working on GaAs. We had arrived independently at the goal of making a semiconductor laser, but with two different crystals: GaAs and GaAsP. I pointed out cleaving to him (and in Syracuse to a slow GE patent attorney) to make diode cavities, but Hall, unknown to me at the time, a telescope builder in his past, preferred polishing, and I, working with large-grain polycrystalline $GaAs_{1-x}P_x$, but single-crystal grain size considerably larger than diode size, preferred cleaving (good idea for single crystal, not so easy for "poly" crystal, random crystal orientation delaying me). Hall should have been cleaving and I polishing, not the reverse. Not just the first to make diode lasers, Hall and I both could have had our two different lasers sooner, maybe as soon as our August 1962 meeting. Always in the beginning we fumble before we gain sufficient experience not to make mistakes. Then, one early 1962 fall day Hall's "boss" (L. Apker) called me (Schenectady to Syracuse) to tell me Hall was running a GaAs laser (IR) [9], its diffraction pattern visible with a "snooperscope," and would I please give up cleaving and polish mirror edges on my nice red p–n junction light emitters that I had shown him on the occasion of an earlier Syracuse company visit? Who knows how much GaAsP crystal and time I wasted before dropping cleaving and turning to polishing to make diode cavity mirrors? I did not quickly grow red-gap GaAsP crystal after Apker's call and make a red diode laser. How could I? That is not how it was done, not in 1960–1962. I had GaAsP. I had been growing GaAsP for a considerable period (since 1960) and (besides tunnel diodes, heterostructures, etc.) making "red" LEDs fully intending, working in the visible, to make after DRC (1962) the first semiconductor laser. I could make a working red GaAsP diode laser as quickly as I could make a cavity, but for my large grain "poly" GaAsP it would have to be by polishing, not cleaving.

After Apker's call I devised at once a simple method (Fig. 2) to polish my GaAsP red-diode Fabry–Perot cavities. I did not know Hall's method until much later and did not like it (too complicated), and he did not like mine (for whatever reason; maybe too simple). Nevertheless, relative to the competition in 1962, we had at GE two different methods of polishing diode laser cavities and

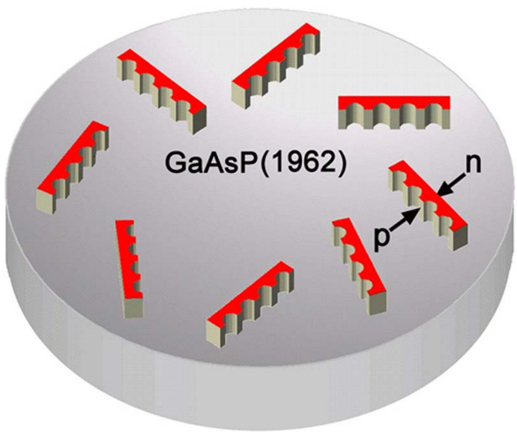

Fig. 2. ***Simple method (Holonyak, GE, October 1962) for polishing Fabry–Perot resonator end mirrors on alloy red-spectrum GaAsP diode lasers. First, a large area Zn-diffused p–n junction, then etched or shallow saw cut into long p–n mesas, next diced at right angles into short mesas still connected in long strips, and finally mounted as shown for mirror polishing.***

cleaving as well, thus three methods, while others elsewhere struggled[1] [24].

Immediately I had (early October 1962) direct-gap ($k_e = k_h$), visible-red, III–V alloy $GaAs_{1-x}P_x$ lasers and LEDs [10] (see also [11] and [12]). The $GaAs_{1-x}P_x$ alloy, a visible-spectrum alloy (!), in the form of a current-driven device, a diode laser and LED, had arrived, proved at once, by the performance and high quantum efficiency, the value of III–V alloys, and indeed became the prototype. Nothing preceded it. The visible spectrum III–V alloys, tunable in energy gap (wavelength), had suddenly become respectable. All high-performance semiconductor lasers and LEDs, in fact, all high-performance III–V semiconductor devices, now employ direct-gap III–V alloys. It is inescapable.

In the end, Hall's and my difference in cavity polishing methods did not matter because we both had good working diode lasers, Hall's IR GaAs and mine visible-red GaAsP, both with high external quantum efficiency, signaling immediately an equally high or higher internal p–n diode (electrical to optical, $\Delta I \cdot V \rightarrow \Delta n \cdot \hbar\omega$) quantum efficiency. Only a small fraction of the (below-threshold) spontaneous e–h recombination, a small "lucky-angle" portion ($\eta_{\text{semi}} > \eta_{\text{air}}$) of a random ($4\pi$ steradian) photon "fog," escaped from a diode in comparison to a high percentage ($\rightarrow$100%) of the stimulated e–h recombination radiation of a diode laser "pointed" directly at a mirror surface. The slower speed of light in the crystal (a dense medium, $\eta_{\text{semi}} > \eta_{\text{air}}$) tends to reflect and trap the photon in the crystal (finally absorbing it) giving only a small "window" (angle) for escape. Stimulated emission (laser operation) first solved the photon extraction problem, reading-out and making apparent the high quantum efficiency of e–h recombination in a direct-gap alloy III–V semiconductor—a p–n diode, in fact, an "ultimate lamp."

The diode laser and its high photon extraction efficiency was the first proof (measured performance) of the high efficiency of diode (p–n junction) recombination radiation. The mechanism (e–h recombination) that carried the current was the mechanism that produced the light, spontaneous or stimulated, approaching ~100% quantum efficiency in the crystal in either case, but not in the photon extraction, which, indeed, could be overcome by stimulated emission (1962) or later by clever crystal device geometry. We (GE) had the lead in knowing this, both in the infra-red (IR, Schenectady) and in the visible (Syracuse), the latter with major implications on LEDs. Band-to-band e–h recombination carried the current across the gap from n-side to p-side ($E_c \rightarrow E_v$, Fig. 1), from negative ($-$) to positive charge ($+$) conduction maintaining continuous end-to-end device current, and across the gap ($E_c \rightarrow E_v$) "switching" the (conduction) charge polarity by e–h recombination producing light. Could anything else be better (sweeter) than the current-carrying mechanism itself, the e–h recombination, the $+/-$ cross-gap change in current polarity, being the light-producing mechanism? We were dealing with an "ultimate lamp," and knew, moreover, that visible-spectrum III–V alloys worked. This was the beginning, whether appreciated or not, of a new era in light generation and lighting. The full importance and benefit of this could not come at once and would take years (decades) to realize fully across the entire spectrum. It is now 50 years later. All the necessary crystal and device science and technology could not be found, could not be invoked immediately. Do managers, politicians, bankers, etc., understand how long it takes to go from the idea world, even ideas that work, to the job world?

VII. WHY AND HOW A SEMICONDUCTOR (DIODE) LASER?

At DRC (New Hampshire, July 1962) [3], [22], we learned a GaAs p–n junction although primitive was nevertheless a surprisingly good source of "light" (e–h recombination radiation, IR), good enough to modulate (ΔI) and send signals (Δlight intensity $= \Delta L \propto \Delta I$) over major distances (~hundreds of yards), but with no hint of how such a copious source of IR "light" might be converted into a laser. Was it even possible? The semiconductor was different, a strongly coupled dense system with a broad e–h band-to-band recombination radiation spectrum ($100 \lesssim \Delta\lambda \lesssim 500$ Å), not a dilute distributed system of discrete elements (atoms, molecules, "quantum well boxes," etc., not coupled or only weakly coupled) with a "sharp" spectral line output ($\Delta\lambda \lesssim 1$ Å). There was no real idea or knowledge of how to convert a rich diode source of spontaneous recombination radiation (an "LED") into a sharp line coherent source. To

[1]At GE, we knew in 1962 that the competition was struggling with the issue of a cavity and how to make it. The "grapevine" was active enough to tell us this, as well as direct information, e.g., the referee question, "Whose polishing equipment did you use"? The very question tells a story.

the extent that the question arose, the idea of a semiconductor laser and the question or need for "discreteness," say, a narrow atom-like spectral line source (the first form of laser, 1960), in many minds simply would not go away, nor the assumed need for a small-scale Manhattan Project to study and make a semiconductor laser. The problem indeed looked formidable, but was mistakenly judged by many as much bigger than it was. Simple solutions made more sense to try first. A good idea was more important than a huge project.

Because of the extensive background that existed (1962) in the world of transistor study and the depth of semiconductor device knowledge, including e–h recombination and light emission and absorption in a semiconductor, some of us knew it was an error to be distracted by the issue of "discreteness" and the need for a large project (why large?), not the right idea of how to proceed, an error in judgment to try somehow to copy earlier lasers (in 1962 still themselves primitive). It was the semiconductor that was of more issue, specifically the high "light" output (in fact, at useful signal levels) of a p–n junction (still primitive), not the need to copy in the case of a dense coupled system (a semiconductor) the operation of a dilute (atomic) system laser (1960), a big system with a low density of active centers. In fact, the earlier laser "builders" were not "players" or the source of any ideas or answers that mattered in the realization of a semiconductor laser, contributing just the fact that light could be coherent (reason enough to thank Ted Maiman, 1960) but contributing nothing about e–h recombination and semiconductor light. There was no direct connection between their work and a diode laser. The significant light output of a direct-gap p–n junction (an IR "LED"), enough to carry a signal and capture our attention, not to mention attract especially our interest and considerable prior understanding of e–h recombination, including stimulated recombination (as well as knowledge of the role of resonators in oscillators), had more to do with the realization of a semiconductor laser than earlier laser knowledge, except that light could be coherent (Maiman, $\omega_{\text{light}} \gg \omega_{\mu\text{wave}}$, $\omega_{\text{light}}/\omega_{\mu\text{wave}} \sim 2 \times 10^4$).

We already know the resolution to the question, the possibility of a semiconductor laser and how in 1962, just months after DRC, GaAs (IR) and GaAsP (visible red) became p–n diode lasers. The diode laser was made apparent with the aid of stimulated emission, a directed output photon beam, not a random photon "fog" trapped by the mismatch (crystal and air) in index of refraction, the high quantum efficiency (→100%) of semiconductor band-to-band recombination radiation. The high efficiency diode laser pointed at once to the fact that the LED too (lower level spontaneous recombination) must have a high internal quantum efficiency. Internally, however, it was absorbing most of the recombination radiation but, eventually, say, in a "proper" device geometry, could reach a high external (output) quantum efficiency. Stimulated emission first "solved" the photon extraction problem from a high index semiconductor material ($\eta_{\text{semi}} \sim 3.5$, $\eta_{\text{air}} \sim 1$), and served as an "existence proof" for future LED performance when a better and better more evolved device geometry could lead to a high photon extraction efficiency at the lower excitation level of an LED (spontaneous recombination). The diode laser (1962) made evident the basis for an "ultimate lamp" (the p–n LED), the prototype being the first visible-spectrum direct-gap III–V alloy GaAsP p–n diode laser and LED.

Fig. 2 reveals, if the GaAsP p–n junction strips are reassembled registered (matched) edge-to-edge mesa-to-mesa in contact in the form of the original crystal, how we started with a large broad area Zn-diffused GaAsP p–n junction "slab," then etched shallow or saw cut deeper long narrow parallel mesas across the large-area p–n junction slab, and next saw cut through the slab accurately at right angles to the slab and to the "long" mesas, giving then the p–n square-edge short-mesa crystal strips of Fig. 2 turned finally on edge and glued ready for Fabry–Perot cavity polishing, finishing with a mirror-to-mirror cavity length of 200–500 μm. A much shorter cavity length (tinier laser) was even possible because of the high gain of a direct-gap ($k_e = k_h$) III–V semiconductor, a unique continous gain condensed matter active region, not a distributed dilute set of more or less low-gain discrete-transition "islands" (hence big laser). Just as the semiconductor prevailed in electronics (electron+hole+ultrasmall connected-device system geometry, the IC), the semiconductor as an "ultimate lamp" laser (electron+hole+photon) could and would prevail. Where the semiconductor competes, it wins, just as in IC memories.

Fig. 3 shows the results: the first (1962) GaAsP III–V alloy visible-red diode laser photographed earlier and again much later on a 2002 penny with a comparison as-grown GaAsP crystal [Fig. 3(a)], and the same p–n GaAsP diode tilted to show more clearly in reflection one of the polished

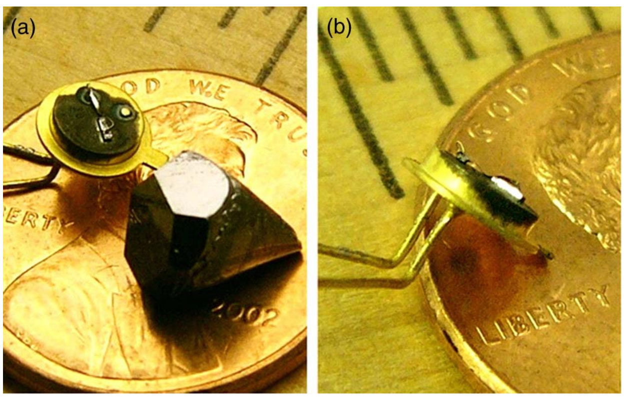

Fig. 3. ***(a) First red-spectrum (October 1962) GaAsP III–V alloy diode laser and a comparison GaAsP ($[GaAs]_{1-x}[GaP]_x$) crystal, photographed often and much later again on a 2002 penny. (b) The first GaAsP diode laser tilted at a more favorable angle to show the reflection of one of the polished mirrors.***

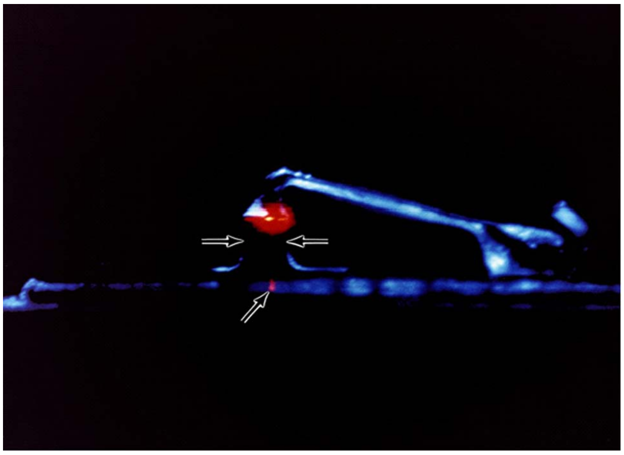

Fig. 4. *First (1962) red-spectrum GaAsP diode laser with its red output photographed directly on film without electrical detector conversion. The yellow spot is the overexposed output-beam center, with the true red coherent signal output shown off-angle at reduced intensity by the lower reflected diffraction spot.*

Fabry–Perot mirror facets of the laser [Fig. 3(b)]. It is interesting to view after 40 years (penny date of Fig. 3) how much the homemade soft n-type alloy attaching the GaAsP p–n junction to the TO-18 header has corroded but, in contrast, not the Au plating, or the III–V crystal, or the annealed Ni lead (bent from handling).

Fig. 4 shows a much deeper saw-cut mesa GaAsP diode laser photographed (1962) directly on film with its own laser light (the first), giving the overexposed "yellow" spot centered on the p–n junction. Actually, the laser output is red as the small lower diffracted beam spot shows. The basis for the LED and "ultimate lamp" had been set and demonstrated (1962), and was the visible-spectrum direct-gap III–V alloy $GaAs_{1-x}P_x$—the prototype.

The "alloy road" to today's LED had started (Figs. 3 and 4). This was reason enough and clearly the time to start abandoning work on indirect-gap ($k_e \neq k_h$) crystal (band-to-band too limited) in favor of direct-gap ($k_e = k_h$) crystal. It was time to begin the search for prospective III–V alloy systems with direct energy gaps extending across the visible spectrum, beyond red to blue and further (III–V/In→ Ga → Al/As → P → N substitution). It was time to start listening to those of us with the data who worked with III–V alloys and direct energy gaps (lasers, as it were), and not indirect gap crystal, not following the folly of "big-lab" insistence on GaP (the kind of poor judgment reminiscent of trying to legislate the value of π).

VIII. THE PRICE OF A SEMICONDUCTOR ("ULTIMATE LAMP") LASER OR LED

There is too much to recount here in full detail, but at once in 1962 with Hall's IR GaAs lasers (coherent radiation) and incoherent emitters and my III–V alloy visible-red $GaAs_{1-x}P_x$ lasers and red LEDs, GE announced late in 1962 the availability of these devices for sale. Because Texas Instruments (TI, Dallas, TX, USA) at the time offered for sale an IR spontaneous recombination GaAs diode at \$130, GE sold GaAs incoherent output (IR) diodes for \$130 and Hall's lasers ten times higher, \$1300, and my red LEDs for \$260 and lasers for \$2600, twice higher. Obviously these prices were set arbitrarily. By the time these devices were listed for sale in the 1965 Allied Catalog [13], the prices were reduced by ~50%. We see how much more valuable GE regarded diode lasers compared to LEDs, and at GE how much more valuable the visible spectrum was considered than IR. Before GE offered diode lasers (at first a company secret) for sale commercially or released manuscripts for publication, a special invited conference was planned and held at Schenectady (November 28, 1962) for representatives of the Defense Department. Maybe there was "need to know." Hall and his colleagues described the GaAs work in the morning, and I the visible alloy GaAsP work in the afternoon session. I also handed out red LEDs assembled in small glass diode packages, packaged (sealed) on the Si diode line in Bldg. 7 in Syracuse. All of my red LEDs vanished in 1962 but not all of my GaAsP lasers, now well picked over.

IX. THE IMPORTANCE OF THE DIRECT-GAP ($k_e = k_h$) AND THE III–V ALLOY

Much more was needed to make the diode laser practical, but the red $GaAs_{1-x}P_x$ LED was practical from the beginning, and only got better and cheaper over time, and became ubiquitous in use, maybe even still being manufactured. It opened the door to what Egon Loebner (H–P→ Agilent → Lumileds → Phillips--Lumileds, and one of the "founders" of the field) later called the "alloy road" to the laser and LED. He was pointing to our work. This was not an easy admission for Egon who, competitive as he was, did not like to give away anything to others. After surviving World War II and a Hitler tattoo, he was in character and bold enough to challenge anything he considered shoddy or incorrect, particularly in optoelectronics, his main interest. When he was dying and had only months to live, he asked me (San Francisco IEEE meeting) to converse with his wife in my parents' language (Carpatho–Rusyn), which for her too was further east than his Czech language. Egon sat calmly smiling instead of, as usual, arguing. Maybe Egon was the first, or at least the clearest or loudest voice, to point out that eventually we must turn to the III–V nitrides (GaN, InGaN, etc.), including alloys, to realize the higher energy of the "blue" [14]. Modern laser-LED researchers have forgotten Egon (why?), but not all of us and, of course, not H–P Lab "old-timers." Egon and I both knew we had to use III–V alloys and, as he admitted, my GaAsP laser and LEDs were the beginning of the "alloy road." The 1962 GaAsP laser and LED was the beginning, the prototype [10]–[12].

I knew at once in 1962 from my red laser, in fact, the first successful III–V alloy device, and its high photon extraction efficiency, pointing to a high internal e–h recombination radiation efficiency, that the route to visible light generation [15] was the direct-gap (e–h wavevector $k_e = k_h$, Fig. 1) III–V alloy family of materials. In other words, alloys work and my visible laser was the proof. And, it is the alloy, the family of III–V alloys, that can be "tuned" in composition across the spectrum and even be made, not necessarily at once, not necessarily fast, but eventually with the help of many people into a wide range of heterojunctions and enhanced performance. It is something still not finished, still happening.

X. THE p–n JUNCTION "ULTIMATE LAMP"

There remained still another issue that bothered me (1962) and that was to prove that the p–n junction was basically an "ultimate lamp." I did not want to take GE, say, "Lamp Department," falsely down the wrong path. In other words, does an "ultimate lamp" imply or require a p–n junction? Is the concept even known: "ultimate lamp," no energy loss in generating light except, of course, for inevitable electrical current resistive loss? I knew from my red III–V alloy p–n diode laser that at lower level (lower current spontaneous recombination) the red LED was basically an "ultimate lamp," but I wanted also a conceptual proof. I was able to show this rather soon based on first principles. Starting with an undoped crystal, which we hold flat-band (e–h +/− neutral) under photoexcitation (light-in for light-out, light generating light, a quantum "in" for a quantum "out," 100% quantum efficiency, a photon "out" for a photon "in") and wish to shift uninterrupted, unchanged flat-band neutral to current excitation, we are forced in order to generate e–h recombination light into doping the crystal (say, by impurity implantation), from right and left into a p–n configuration (Fig. 1) in order to realize (with external voltage bias, $qV \sim E_g \sim \hbar\omega$) a directly current-driven "ultimate lamp." We need to make a p–n junction. We need to bias and drive the E_g recombination crossover, the gap, with an external source and voltage (the equivalent of photoexcitation), a source of e–h current (Fig. 1, e on the right, h on the left), and then eliminate (remove) photoexcitation. By the end of the exercise, maintaining throughout flat-band "neutrality," we have lifted the photoexcitation and have shifted seamlessly to current excitation, needing (constructing) in the end a p–n junction (Fig. 1) to bridge current via injection and recombination across the gap (a direct gap, $k_e = k_h$, $\Delta k = 0$) from electron (−) to hole (+) conduction (still 100% quantum efficiency as in photoexcitation). Later I frequently taught the argument to graduate students, and eventually published a small proof [16], [17], showing that an "ultimate lamp" of necessity takes the form of a p–n junction. It was all a consequence of the transistor and the need to study e–h recombination, the transistor base current.

XI. FURTHER CONTRIBUTIONS

Now after so much work (~50 years), of so many people, some of my former students first at Monsanto and then Philips–Lumileds, some solving the problem of photon extraction from an incoherent source, the lower current level LED complement to the high extraction efficiency of my coherent-output visible lasers, and, of course, the work of many others around the world, the high-brightness, high-performance LED that now promises to take over lighting is, in fact, based entirely on the direct-gap III–V alloy (on the III–V alloy family), as well as on the quantum well(s) that we introduced into diode lasers and LEDs 35+ years ago (Fig. 5 [18]).

QW modification of semiconductor lasers and LEDs is still happening. If we examine again the Monsanto LED advertisement of 40 years ago (Fig. 6), which at the time for me (a Monsanto consultant) and George Craford (then Monsanto LED lab director) drew biting criticism from a leading competing big LED research group, admonishing us: "We are leaders in LED research and know the LED; we know and you know your advertisement is wrong; LEDs will never be on the "front-end" of cars; you, the technical advisors, should know better." We see now whether Monsanto was well advised or just clairvoyant or just enthusiastic in placing such an advertisement, which had nothing to do, as a matter of fact, with me or George Craford. But is this, the 40 year old (1971) Monsanto advertisement, the Monsanto view of the LED, a surprise since the concept of an "ultimate lamp," the p–n LED, goes back even further, ~50 years to 1962 and GaAsP III–V alloy p–n diode laser data? The promise of a p–n LED

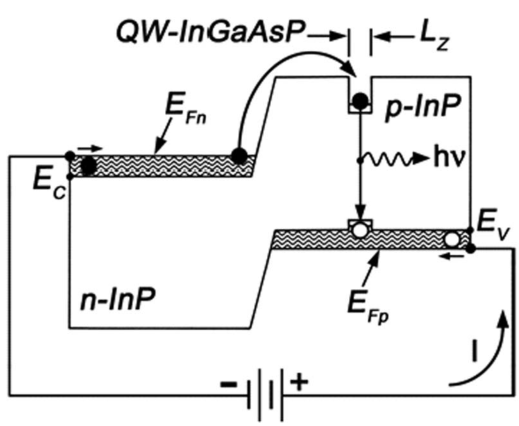

Fig. 5. *Diagram of first (1977, [18]) quantum-well (QW) p–n diode laser InP(n)–InGaAsP$_{QW}$–InP(p), a high-level (large current) p–n "ultimate lamp." In the LPE fabrication process, the Zn-doping on the p-type side drifted across the QW and offset the QW, remaining however still effective in collecting and recombining electrons.*

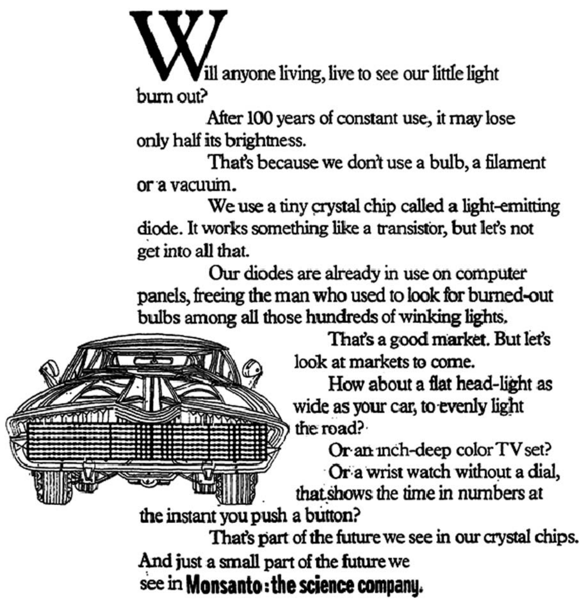

Fig. 6. ***Monsanto LED advertisement ~40 years ago projecting what was then perceived as the LED future, an advertisement that drew major criticism of Craford (Monsanto lab director) and Holonyak (consultant) from several "big" lab directors of eventually doomed indirect-gap*** $(k_e \neq k_h)$ ***GaP LED projects.***

"ultimate lamp" was not nearly as ill-founded and unproven as that of a practical fusion reactor projected to generate unlimited energy.

We can at this point compress the entire ~50 year p–n III–V alloy diode laser-LED study into a single figure (Fig. 7). It slants from its beginning in the lower left-hand corner (1962) to now ~50 years later to the upper right hand corner of the "ultimate lamp," 100% conversion of electrical to optical energy except for ohmic loss. It was the GaAsP alloy work, laser and LED, that got "it" all started and pointed at what an "ultimate lamp" would be, of necessity basically a p–n junction. The GaAsP laser, the start, is shown symbolically in a bulb on the left leading to the symbol of an LED in a bulb. The bulb, as such, the incandescent lamp, a much better heat source than light source, is obviously obsolete. The stimulated recombination of the laser (~100% quantum efficiency), because of its high photon extraction efficiency, revealed the high efficiency of alloy III–V p-n junction recombination radiation, and what would be the future of the LED. From lower left to upper right in Fig. 7 we see the long difficult step by step slow progress in going from longer to shorter wavelengths (red → orange → yellow → green → blue) toward higher and higher light output (lumens/Watt) and an "ultimate lamp." Bit by bit indirect-gap $(k_e \neq k_h)$ crystal lost in importance to direct-gap $(k_e = k_h)$ III–V alloys; in the end, as could be predicted (1962 and GaAsP), the direct-gap III–V alloy prevailing, big lab decisions and arguments notwithstanding. The blue end of the spectrum came later informed by all that had been learned at longer wavelengths (see Fig. 7), including the importance of a direct gap $(k_e = k_h)$, III–V alloys, QWs, Mg (p) doping, and the Dupuis-style of MOCVD crystal growth, which now prevails.

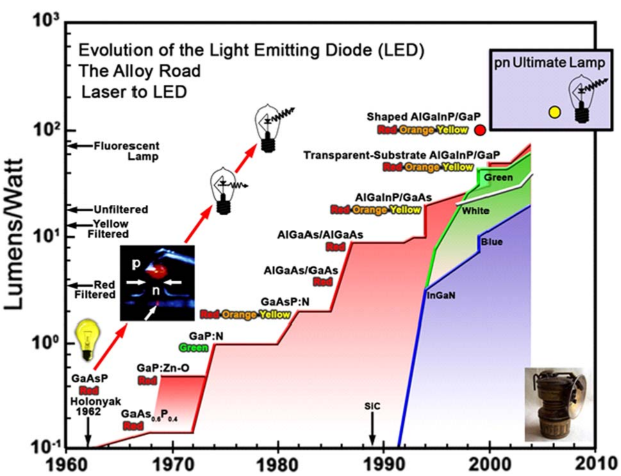

Fig. 7. ***The ~50 year evolution from the (1962) p–n direct-gap*** $(k_e = k_h)$ ***red-spectrum III–V alloy diode laser (and its high photon extraction efficiency) to the p–n direct-gap III–V alloy QW LED "ultimate lamp." Direct-gap mattered and prevailed, and indirect-gap*** $(k_e \neq k_h)$ ***was a poor choice and not basis for an "ultimate lamp."***

I want to mention that almost all the high-performance III–V alloy lasers and LEDs (QW devices) being made today employ the MOCVD crystal growth process pioneered (1977) by my former student and now colleague for many years R. D. Dupuis. I should mention also the LED work of other of my former students: M. G. Craford at Monsanto using the nitrogen trap in GaAsP made the first practical yellow LEDs; M. J. Ludowise at Varian purified and first used Mg (p) doping successfully in MOCVD III–V crystal growth; F. A. Kish at H–P solved the problem of large-scale transparent-substrate replacement on the LED and reduced the internal-device photon absorption; M. R. Krames at H–P Lumileds first solved the crystal geometry problem of LED spontaneous recombination radiation escape; and in Urbana (~1970), we demonstrated the red–orange–yellow laser-LED operation of the alloy InGaP, later extended to In(AlGa)P by Dupuis-MOCVD. In Fig. 8, Bardeen and I (~1970) are looking at our (Urbana) early red–orange–yellow InGaP LEDs, well before Dupuis' successful vapor-phase MOCVD Al–Ga substitution had been accomplished and changed the field. And, of course, others have added their part. The diode laser and LED started "small" but is now a World enterprise, and in performance becoming an actual "ultimate lamp." Anything less than an "ultimate lamp" is doomed to be replaced.

Based on a fundamental point of view, what is happening now to the diode laser and LED is not surprising, just the magnitude, just the scale, and variety of LED development and use. Since we are talking about an "ultimate lamp" (diode laser or LED), this work will not stop, will

Fig. 8. ***Bardeen and Holonyak in 214 EERL (Urbana, 1970–1971) examining ($k_e = k_h$, laser-quality crystal) red–orange–yellow (ROY) $In_{1-x}Ga_xP$ LEDs that became, with the Al–Ga substitution of Dupuis MOCVD crystal growth, $In_{1-x}(Ga_{1-y}Al_y)_xP$ QW p–n LED "ultimate lamps."***

Fig. 9. ***Left to right (bottom) Holonyak and Feng and (top) Chan and Walter, and in the background the symbol for the transistor laser (TL) first realized in Urbana (after [19]).***

only grow, develop further, take on still more variety, become vaster and vaster, and, of necessity, become cheaper, making possible universal use of the LED, consequently appearing everywhere in lighting and decorating. Why not? How can an "ultimate lamp," now realizable, and being worked on by so many, be denied?

Finally, I want to add another comment: Since the diode laser and LED are now almost 50 years old, and occupy two or more generations of work, I suspect many current workers fail to see what the connection is to the now almost 65-year-old transistor. Nevertheless, thinking about the transistor, in fact, about Bardeen and Brattain's 1947 "only-a-base-crystal" transistor, inherently bipolar and using e–h recombination, just a primitive "chunk" of n-type germanium and hardly any technology, hence so revealing, focusing attention on what really matters, focusing on the base, my colleague M. Feng and I, with our postdoctoral and graduate students (Walter, Chan, Then, *et al.*) have reinvented the transistor into a three-terminal QW transistor laser [19]. Fig. 9 shows left to right (bottom) Holonyak and Feng and top Chan and Walter, and in the background (top) the Urbana symbol for the transistor laser (TL). The transistor laser might be the most important thing that has happened to the transistor since the transistor. This development, a further extension of semiconductor light and electronics, is based on the fundamental role and importance of the transistor "base" current and its dependence on e–h recombination, all very clear from the simple form of Bardeen and Brattain's original 1947 transistor, the transistor reduced to its essence, in the beginning just a base crystal. It still informs us.

The point is, not only have all the principles of semiconductor device operation, including all the circumstances of e–h recombination and light generation, not been fully determined or elucidated in almost 60 years (witness the transistor laser, the transistor reinvented, connected electrically and optically, and taken further), we are not even close to solving all the difficult crystal and materials problems (all the doping and device "geometry" problems) involved in realizing more and more sophisticated diode lasers, LEDs, and now transistor lasers—and then on the "parent" semiconductor crystal platform "tying" all of these together at ultrasmall size as ICs. The semiconductor (electron+hole+photon), a dense high-gain electrical–optical atomic system (an extended well-ordered giant atomic system), is alive and well, not finished, and under no threat to be replaced. Nothing else has been quite so universal in electronics. Nothing else has offered so much. For example, nanoscale substance, unconnected small-geometry substance, still lacking so much both practically and fundamentally, is not much of a threat to the p–n III–V alloy laser, LED, or transistor laser, and to the fact that all of these QW device elements are capable of

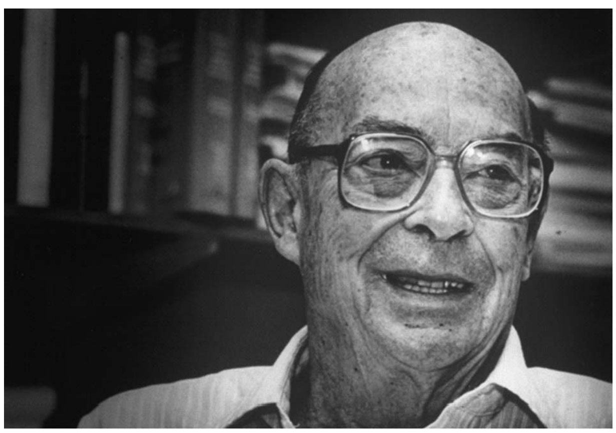

Fig. 10. ***John Bardeen at ~80 (~1988).***

coming together as higher and higher performance monolithic optoelectronic ICs. The conclusion is simple: the semiconductor is here to stay. ■

Acknowledgment

I wish to mention we are all in John Bardeen's (and Walter Brattain's) debt for the transistor, some of us even more so for Bardeen bringing (1951) semiconductor research to Urbana and for the school of work he started. In Fig. 10, we show John Bardeen at ~80 (~1988) in his office still working.

I am grateful to M. Feng for many discussions on lasers, LEDs, and transistor lasers (the electronics and optoelectronics of the electron+hole+photon) and to G. Walter for his contributions to the transistor laser and for his rendering of many of the figures, and, of course, to my many grad students who have done so much.

REFERENCES

[1] J. Bardeen and W. H. Brattain, "The transistor, a semi-conductor triode," *Phys. Rev.*, vol. 74, pp. 230–232, Jul. 1948.

[2] T. H. Maiman, "Stimulated optical radiation in ruby," *Nature*, vol. 187, pp. 493–494, Aug. 6, 1960.

[3] R. J. Keyes and T. M. Quist, presented at the IRE Solid State Device Res. Conf., Durham, NH, USA, Jul. 1962.

[4] N. Holonyak Jr., "Use of metallic halide as a carrier gas in the vapor deposition of III–V compounds," U.S. Patent 3 249 473, May 3, 1966.

[5] N. Holonyak, Jr., "Double injection diodes and related DI phenomena in semiconductors," *Proc. IRE*, vol. 50, no. 12, pp. 2421–2428, Dec. 1962.

[6] J. S. Blakemore, *Semiconductor Statistics*. New York, NY, USA: Pergamon, 1962, pp. 183–189196–202.

[7] P. J. Corso, *The Day After Roswell*. New York, NY, USA: Pocket Books, 1997, pp. 301–303.

[8] A. Jacobsen, *Area 51*. New York, NY, USA: Little, Brown and Co., 2011.

[9] R. N. Hall, G. E. Fenner, J. D. Kingsley, T. J. Soltys, and R. O. Carlson, "Coherent light emission from GaAs junctions," *Phys. Rev. Lett.*, vol. 9, pp. 366–368, Nov. 1, 1962.

[10] N. Holonyak, Jr. and S. F. Bevacqua, "Coherent (visible) light emission from $Ga(As_{1-x}P_x)$ junctions," *Appl. Phys. Lett.*, vol. 1, pp. 82–83, Dec. 1, 1962.

[11] N. Holonyak, Jr., "Semiconductor alloy lasers—1962," *IEEE J. Quantum Electron.*, vol. QE-23, no. 6, pp. 684–691, Jun. 1987.

[12] N. Holonyak, Jr., "The semiconductor laser: A 35 year perspective," *Proc. IEEE*, vol. 85, no. 11, pp. 1678–1693, Nov. 1997.

[13] Allied Industrial Electronics Cat., No. 650, Chicago, IL, USA, 1965, p. 77.

[14] E. Loebner, "Subhistories of the light emitting diode," *IEEE Trans. Electron Devices*, vol. ED-23, no. 7, pp. 675–699, Jul. 1976.

[15] H. Manchester, "Light of hope—Or terror," *Reader's Dig.*, vol. 82, no. 490, pp. 97–100, Feb. 1963.

[16] N. Holonyak, Jr., "Is the light emitting diode (LED) an ultimate lamp?" *Amer. J. Phys.*, vol. 68, pp. 864–866, Sep. 2000.

[17] N. Holonyak, Jr., "The semiconductor p-n junction ultimate lamp," *MRS Bull.*, vol. 30, pp. 515–517, Jul. 2005.

[18] E. A. Rezek, H. Shichijo, B. A. Vojak, and N. Holonyak, Jr., "Confined-carrier luminescence of a thin $In_{1-x}Ga_xP_{1-z}As_z$ well ($x \sim 0.13$, $z \sim 0.29$; ~ 400 Å) in an InP p-n junction," *Appl. Phys. Lett.*, vol. 31, pp. 534–536, Oct. 15, 1977.

[19] M. Feng and N. Holonyak, Jr., "The metamorphosis of the transistor into a laser," *Opt. Photon. News*, vol. 22, no. 3, pp. 44–49, Mar. 2011.

[20] J. Bardeen and W. H. Brattain, "Three-electrode circuit element utilizing semiconductive materials," U.S. Patent 2 524 035, Oct. 3, 1950.

[21] T. H. Maiman, "Ruby laser systems," U.S. Patent 3 353 115, Nov. 14, 1967.

[22] R. J. Keyes and T. M. Quist, "Recombination radiation emitted by gallium arsenide," *Proc. IRE*, vol. 50, no. 8, pp. 1822–1823, Aug. 1962.

[23] N. Holonyak, Jr., D. C. Jillson, and S. F. Bevacqua, "Halogen vapor transport and growth of epitaxial layers of intermetallic compounds and compound mixtures," in *AIME Conf. (August 1961), Los Angeles*, vol. 15, J. B. Schroeder, Ed. New York, NY, USA: Interscience, 1962, pp. 49–59.

[24] H. Zeiger, "The prehistory of the laser and beyond," *Opt. Photon. News*, vol. 15, no. 5, pp. 14–15, May 2004.

ABOUT THE AUTHOR

Nick Holonyak, Jr. (Life Fellow, IEEE) was born in November 1928 in Zeigler, IL, USA. He received the B.S., M.S., and Ph.D. degrees in electrical engineering from the University of Illinois at Urbana-Champaign, Urbana, IL, in 1950, 1951, and 1954, respectively.

He was John Bardeen's first student and held a TI fellowship. He worked at Bell Telephone Laboratories (1954–1955) and, after military service, at GE (Syracuse, NY, USA, 1957–1963) before returning in 1963 to the University of Illinois. He is John Bardeen Chair Professor of Electrical and Computer Engineering and Physics, and Electrical and Computer Engineering Professor in the Center of Advanced Study. He is an early contributor (1954–1960) to diffused-impurity oxide-masked silicon device technology (transistors, p-n-p-n switches, and thyristors), the technology basic to the integrated circuit (IC). He is the inventor (1958) of the shorted emitter used in thyristors and symmetrical switches (TRIACs), including the basic element in the wall light dimmer. He is the first to make silicon tunnel diodes and observe phonon-assisted tunneling (1959), the first observation of inelastic tunneling and the beginning of tunneling spectroscopy. He invented (1960) closed-tube vapor-phase epitaxy (VPE) of III–V semiconductors, the forerunner of present-day open-tube III–V VPE crystal growth. Besides early work (1960–1962) on III–V heterojunctions, he was the first (1960) to grow $GaAs_{1-x}P_x$ (an alloy) and to construct visible-spectrum lasers and light-emitting diodes (1962), thus proving that III–V alloys are "smooth" and viable, in general, for use in optoelectronic devices. He is the inventor of the first practical LED, the red $GaAs_{1-x}P_x$ LED, which (based on its diode laser extension) led to the concept of an "ultimate lamp" and marks also the beginning in the use of III–V alloys in semiconductor devices, including in heterojunctions and quantum-well heterostructures (QWHs). Besides demonstrating the visible-spectrum laser operation of the alloys GaAsP (1962), InGaP (1970), AlGaAsP (1970), and InGaPAs (1972), he and his student Rezek made (via LPE, 1977) the first quantum-well (QW) diode lasers. Later, with Dupuis (and MOCVD AlGaAs-GaAs), he demonstrated (1978) the initial continuous 300-K operation of a QW laser, and introduced the name "quantum-well laser." He and his students introduced (1980) impurity-induced disordering and intermixing (~600 °C) of QWH and superlattice layers, and with it the selective shift from QW lower gap to bulk-crystal higher gap (used to define waveguide and laser geometries). In 1990, he and his students introduced the Al-based III–V native oxide into optoelectronics, including its use as a buried oxide aperture to define the current and cavity in lasers (now used in VCSELs). He (with Dupuis) introduced coupled quantum-dot/quantum-well lasers, and with M. Feng introduced light-emitting heterojunction bipolar transistors (HBLETs) modified with quantum-well base regions and reinvented the transistor as a transistor laser (2004). His work has led to over 574 papers and 55 patents.

Prof. Holonyak is a member of the National Academy of Engineering (1973), the National Academy of Sciences (NAS, 1984), the American Academy of Arts and Sciences (Fellow, 1984), the Russian Academy of Sciences (Foreign Member, 1999), the American Physical Society (Fellow), the Optical Society of America (OSA, Fellow), the American Association for Advanced Science (Fellow), the Electrochemical Society, and the Mathematical Association of America. He has received a number of awards, including: the Cordiner Award (1962, GE); the Morris N. Liebmann

Award (1973, IEEE); the John Scott Medal (1975, City of Philadelphia); the Gallium Arsenide Symposium Award with Welker Medal (1976); the Jack A. Morton Award (1981, IEEE); the Solid State Science and Technology Award (1983, the Electrochemical Society); the Monie A. Ferst Award (1988, Sigma Xi); the Edison Medal (1989, IEEE); the National Medal of Science (1990, the United States); the Charles H. Townes Award (1992, OSA); the Honorary Member of the Ioffe Physical-Technical Institute (1992, St. Petersburg); the Honorary Doctor of Science (1992, Northwestern University); the NAS Award for the Industrial Application of Science (1993); the ASEE Centennial Medal (1993); the American Electronics Association 50th Anniversary Award (1993); the Vladimir Karapetoff Eminent Members' Award of Eta Kappa Nu (1994); the Honorary Doctor of Engineering (1994, Notre Dame); the TMS John Bardeen Award (1995, The Minerals, Metals, and Materials Society); the Japan Prize (1995); the Eminent Member of Eta Kappa Nu (1998); the Distinguished Alumnus of Tau Beta Pi (1999); the IEEE Third Millennium Award (2000); the Frederic Ives Medal of the Optical Society of America (2001); the Global Energy International Prize (Russia, 2003); the IEEE Medal of Honor (2003); the National Medal of Technology (2002 Medal, awarded 2003); the Washington Award (Western Society of Engineers, 2004); the Lemelson—MIT Prize (2004); the MRS Von Hippel Award (2004); the Izaak Walton League of America Illinois Division Energy Conservation Award (2004); the Laureate of the Lincoln Academy of Illinois (2005); the Member of the Consumer Electronics Association (CEA) Hall of Fame (2006); the National Inventors Hall of Fame (2008); The Engineering at Illinois Hall of Fame (2010); and the Engineering and Science Hall of Fame (2011).