CC/NUMBER 52
DECEMBER 28, 1981

This Week's Citation Classic

Holonyak N, Jr. Double injection diodes and related DI phenomena in semiconductors. *Proc. IRE* **50**:2421-8, 1962.
[Advanced Semiconductor Lab., Semiconductor Products Dept., General Electric Co., Syracuse, NY]

Double injection (DI), with negative resistance, could have been observed in semiconductors in the early-1950s when R.N. Hall first created the p-i-n diode.[1] The experimental identification of DI occurred ten years later on semi-insulating GaAs, and was then confirmed on Au-doped Si. [The *SCI*® indicates that this paper has been cited over 125 times since 1962.]

Nick Holonyak, Jr.
Department of Electrical Engineering
and
Center of Advanced Study
University of Illinois
Urbana, IL 61801

November 9, 1981

"In the late-1950s and early-1960s some of us who had worked earlier on Si technology had, for good reason, turned to work on ill-V semiconductors. Silicon, as important as it is, is by no means an ideal material. GaAs and related Ill-V's offered, even in 1959-1962, certain desirable properties. One of these special properties that we tried to exploit in 1961-1962 was its semi-insulating behavior. Multiple diodes, made with epitaxial techniques[2] or conventional acceptor diffusion and Sn (donor) alloying, could be fabricated on a single substrate. These DI diodes exhibited negative resistance, which at first seemed puzzling and not at all like Hall's classic p-i-n diode.[1] I recalled, however, Murray Lampert explaining (theory) to us in 1961 at a meeting (Device Research Conference, Stanford) the peculiarities of DI.[3,4] I realized that DI had to explain our results, and to confirm that this was basically correct I turned back to look at Si. I asked a colleague (R.C. Thomas) in our crystal-growth section to find a piece of Au-doped Si (which I knew he possessed), to etch a piece, to alloy Au-Sb (n) on one side and Al-B (p) on the other, and to check the resulting diode (a p-'i'-n) for negative resistance and unusual photosensitivity. Although we were quickly convinced, we had a difficult time proving our point to a stubborn *Physical Review Letters* referee. After I called the editor, he stated he would take our manuscript to a Physical Society meeting in Washington and see what comments he could elicit. We did not hear further from him; our manuscript was published outright.[5] We did much more detailed work and I presented our results at the 1962 IRE Solid State Device Research Conference (SSDRC) and wrote the paper at hand. A number of colleagues, at General Electric and other organizations, remarked that frequently they had accidentally seen p-i-n's with negative resistances, but weren't sure why. They were happy to see that the DI identification had been experimentally accomplished.

"The events of the 1962 IRE SSDRC caused a number of us to go home to try to build a semiconductor laser. I felt strongly that a semiconductor laser should be made in the visible and by the fall of 1962 (because of my knowledge of how to grow vapor phase epitaxial Ill-V alloys)[2] constructed a GaAsP red laser diode. The results were published in *Applied Physics Letters.*[6] On a lark, I entered a reprint of this paper and of the *Proceedings of the IRE* DI paper into an IRE Syracuse-section competition, and won. When I asked and learned that it was for the DI paper, I was disappointed, particularly when the Syracuse-IRE official dismissed the laser paper as 'not much.' I knew (1962) that a red laser diode was the basis for a red LED, and that only an ignorant person would consider the DI work more important. Of course, I regarded the DI work as important, but not nearly as important as the GaAsP laser-LED, or a dozen or more projects that have concerned me in the last 30 years.

"I think our DI work has survived and been of value because it came early, finally showed experimentally the nature of DI, provided rather extensive data on various materials (GaAs, Si, Ge) doped with various traps, and was probably the first place that readers heard of impurities like Co in Si as well as the great photosensitivity of Si:Zn."

1. **Hall R** N. Power rectifiers and transistors. *Proc. IRE* 40:1512-18, 1952.
2. **Holonyak N, Jr., Jillson D C & Bevacqua** S **F.** Halogen vapor transport and growth of epitaxial layers of intermetallic compounds and compound mixtures. (Schroeder J B, ed.) *Metallurgy of semiconductor materials.* New York: Interscience, 1962. Vol. 15. p. 49-59.
3. **Lampert** M A. Double injection in insulators. *Phys. Rev.* 125:126-41, 1962.
4. **Lampert M A & Mark P.** *Current injection in solids.* New York: Academic Press, 1970. 351 p.
5. Holonyak N, Jr., Ing S W, Jr., Thomas R C & **Bevacqua** S **F.** Double injection with negative resistance in **semi-insulators.** *Phys. Rev. Lett.* **8:426-8. 1962.**
6. Holonyak N, Jr. & **Bevacqua** S F. Coherent (visible) light emission from $Ga(As_{1-x}P_x)$ junctions. *Appl. Phys. Lett* 1.82-3, 1962. [The *SCI* indicates that this paper has been cited over 95 times since 1962.]