This Week's Citation Classic

Oldham W G & Milnes A G. Interface states in abrupt semiconductor heterojunctions. *Solid State Electron.* 7:153-65, 1964.
[Dept. Electrical Engineering, Carnegie Inst. Technology, Pittsburgh, PA]

The expected electrical consequences of the dislocation network required at heterojunction interfaces is examined. For lattice mismatches of greater than about one percent, interface states should dominate the electrical properties of the junction. Experiments on n-n and p-p Ge-Si heterojunctions bear out the expectations. [The *SCI*® indicates that this paper has been cited in over 90 publications since 1964. Of these, 43 occurred in the period, 1973-1983.]

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"About 1960, Donald Feucht and Arthur Milnes initiated a program aimed at the understanding of semiconductor heterojunctions. W.G. Oldham joined several graduate student friends, including Joseph Donnelly, Stuart Perlman, and Arthur Riben, in this interesting new area of device physics. We grew and investigated a variety of heterojunctions between combinations of III-V compounds, Ge and Si. It seemed that the ideal heterojunction, i.e., one really following the Anderson model,[1] eluded us. In fact, it was much later that the technology and understanding were sufficient for practical application.

"In the beginning, a good deal of the work involved chasing down the causes of 'nonideal' behavior. In the paper cited here, we had to account for anomalous I-V and C-V characteristics of Ge-Si interfaces. By changing the junction types and doping, all the unknown variables could be potentially eliminated. The results could not be explained by simple heterojunction theory.[1] The obvious explanations of contaminated interfaces were largely precluded by the growth technique—low temperature epitaxy on an *in situ* cleaved surface. The cleaving technology was inspired by the photoemission studies of Allen and Gobeli.[2] The interpretation of the results was also influenced by their results—large densities at a free Si surface, essentially pinning the Fermi level. The pioneering works of Bardeen on Ge surface states[3] and Read on electrical effects of dislocations[4] led us to the now obvious conclusion that the (then presumed) interfacial network of lattice-matching dislocations would dominate the electrical properties of the heterojunction between materials with significant lattice mismatch.

"The subsequent interest in this early paper owes largely to the foresight of Feucht and Milnes in initiating the heterojunction research when they did. Anderson's work provided a theoretical framework,[1] and Marinace demonstrated a simple experimental technique for epitaxial growth.[5] The time was ripe, and each experiment led to new understanding. It is, however, puzzling to us that there are any recent direct citations to the work of this period. In 1972, Milnes and Feucht published an excellent comprehensive monograph which summarized the heterojunction work to date.[6]

"Appropriately, Milnes recently received the J.J. Ebers Award of the IEEE Electron Devices Society in recognition for outstanding contributions to electron devices."

1. **Anderson R L.** *Germanium gallium arsenide contacts.* PhD thesis. Syracuse, NY: Syracuse University, 1960.
2. **Allen F G & Gobeli G W.** Work function, photoelectric threshold, and surface states of atomically clean silicon. *Phys. Rev.* **127**:150-8, 1962. (Cited 215 times.)
3. **Bardeen J.** Surface states and rectification at a metal semi-conductor contact. *Phys. Rev.* **71**:717-27, 1947. (Cited 355 times.)
4. **Read W T, Jr.** Theory of dislocations in germanium. *Phil. Mag.* **45**:775-96, 1954. (Cited 225 times.)
5. **Marinace J C.** Epitaxial vapor growth of Ge single crystals in a closed-cycle process. *IBM J. Res. Develop.* **4**:248-55, 1960. (Cited 65 times.)
6. **Milnes A G & Feucht D L.** *Heterojunctions and metal-semiconductor junctions.* New York: Academic Press, 1972. 408 p. (Cited over 380 times.)