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This Week's Citation Classic

Stern F & Howard W E. Properties of semiconductor surface inversion layers in the electric quantum limit. *Phys. Rev.* **163**:816-35, 1967.
[IBM Thomas J. Watson Research Center, Yorktown Heights, NY]

Quantization effects on energy levels and on transport properties of electrons in semiconductor space-charge layers are investigated, including the consequences of anisotropic, multi-valley conduction bands. Screening effects and binding to a Coulomb potential are also discussed. [The *SCI*® indicates that this paper has been cited in over 510 publications since 1967.]

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"Strong electric fields at the semiconductor-insulator interface in metal-insulator-semiconductor (MOS) structures confine carriers to a narrow layer near the interface and are expected to lead to quantum effects, as first pointed out by Schrieffer[1] in 1956. He thought that level broadening associated with surface scattering would wash out the effects. Nevertheless, many workers—especially in the mid-1960s—tried to interpret various transport results in terms of quantum effects.

"Only after Alan Fowler, Frank Fang, Webster Howard, and Phillip Stiles[2] applied a magnetic field perpendicular to the surface and saw evenly spaced oscillations in conductance as the carrier concentration was increased (as expected for a two-dimensional electron gas in which the Fermi level moves past the Landau levels) was the quantization clearly confirmed. At the time of this experiment, early in 1966, I was away on a one-year assignment at the IBM Zurich Research Laboratory. I began calculations on this system soon after my return to Yorktown Heights in July. It was to be the most intense year of scientific activity of my career.

"I approached the system as the two-dimensional analog of a bulk semiconductor, for which most of the conventional results would have to be rederived. Many of the properties of such a two-dimensional system were already understood by Howard, who had been working with Fang on MOS devices since 1964 and had already carried out self-consistent calculations of energy levels. Howard and I worked on the carrier statistics; on the energy level structure for a general surface orientation taking into account the anisotropic, multi-valley conduction bands of silicon and germanium; on phase-shift and Born-approximation treatments of scattering; on static screening by inversion layer electrons; and on a primitive model for bound states associated with Coulomb centers.

"Only a few groups, including some in Germany and Japan, took note of our work at first. The 20-odd people who attended the US-Japan Seminar on Surface Quantization and Transport in Honolulu in 1972 included members of most of the active groups. Interest in two-dimensional systems then began to grow rapidly as many-body effects were calculated in detail and as cyclotron resonance and optical absorption experiments confirmed some aspects of the theory and pointed to new problems. The field continues to flourish. A recent review of electronic properties of two-dimensional systems by Tsuneya Ando, Fowler, and me,[3] with about 1,900 references, is already being superseded by new results in aspects such as weak localization and quantized Hall conductance.

"The paper by Howard and me has been widely cited because it gave the first systematic account of the properties of electrons in inversion layers. It probably contributed to my being included with Fang, Fowler, Howard, and Stiles in the award by the Franklin Institute of the John Price Wetherill Medal in 1981."

1. **Schrieffer J R.** Mobility in inversion layers: theory and experiment. (Kingston R H, ed.) *Semiconductor surface physics.* Philadelphia: University of Pennsylvania Press, 1957. p. 55-69.
2. **Fowler A B, Fang F F, Howard W E & Stiles P J.** Magneto-oscillatory conductance in silicon surfaces. *Phys. Rev. Lett.* **16**:901-3, 1966.
3. **Ando T, Fowler A B & Stern F.** Electronic properties of two-dimensional systems. *Rev. Mod. Phys.* **54**:437-672, 1982.