This Week's Citation Classic

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Hilsum C & Rees H D. Three-level oscillator: a new form of transferred-electron device. *Electron. Lett.* **6**:277-8, 1970.

Field-excited electron transfer between three sets of energy levels gives more pronounced negative resistance effects than the two-level transfer used previously. The neglected semiconductor, indium phosphide, should operate in this way, and would give higher efficiency microwave sources than the standard material, gallium arsenide. [The *SCI*® indicates that this paper has been cited over 105 times since 1970.]

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"I suppose every scientist is flattered when his publications are quoted widely, and my colleague, David Rees, and I are certainly pleased that we broadened an already important field. However, our pleasure must be somewhat muted by the realisation that many people who quote our work do so while believing a good part of it to be wrong!

"Our group at the Royal Signals and Radar Establishment has been involved since 1965 in theoretical and experimental research on high electric field effects in semiconductors. Throughout the 1960s the work was concentrated almost completely on one semiconductor, gallium arsenide, because this material shows a pronounced negative differential resistance at fields above about 3500 volts/cm. This means that a thin piece of GaAs driven with a few volts DC becomes electrically unstable, and oscillates at a high frequency. It gives an extremely simple source of microwave radiation, albeit with a conversion efficiency of only 10% or so. The combination of fascinating physics with lucrative commercial applications does not occur too often, and our group was happy for some years developing new theoretical techniques for calculating the properties of electrons at high fields-hot electrons and perfecting the device structures for generating microwaves.

"The negative resistance appears because the hot electrons are forced by the field from one set of electronic states to another. The high energy states, empty at low fields, are much less conductive. Curiously then, the higher the field, the higher the fraction of non-conducting electrons, and the lower the current.

"By the late 1960s we were perhaps a little saturated with GaAs, and conscious that our research was becoming pedestrian. Development of semiconductor microwave sources was well under way in industry, so our role was no longer critical. We began to think deeply about electron transfer, the process underlying the negative resistance, and wondered if there were more pronounced effects available. There seemed a limited number of options open, because, after all, we could only exploit those electronic states actually built into solids, but we appreciated we could be misusing one opportunity. Previously we had considered transfer between just two sets of energy levels, but there are, in principle, three, though in most semiconductors only two are accessible. A series of calculations showed that such transfer could give a larger negative resistance, and should lead to sources of higher efficiency. The best binary compound, indium phosphide, should show three level transfer, and be a better source than the universally used gallium arsenide. This was essentially the message of this publication.

"Few people believed us. InP had been tried in the early days, and had shown pathetic performance. We felt those experiments were misleading, since the samples must have been impure, but there was only one way of settling the issue. Our group started a long programme on purifying InP and making devices from it. It took five years to prove beyond doubt that very high efficiencies could be obtained.

"Our work has borne fruit, but is there a maggot' Do we actually exploit three levels, or are there more subtle differences between InP and GaAs? Most people vote for two levels, and I suspect I am alone in thinking that the issue is unresolved. My colleagues say they don't care much, since InP works fine. Actually, I haven't asked David what he thinks now.

"By the way, two years ago they changed the assignment of levels in GaAs. If we'd known that in 1970, I doubt if we would have persevered with InP "