"Second Breakdown" in Transistors

This paper [1] provided the first detailed characterization of a serious and, at the time, poorly understood failure mechanism of power transistors, called second breakdown, which could occur well within the power dissipation limits of these devices. It addressed the problem that early transistors (those prior to the bipolar field-effect transistors that are common today) failed while operating well within switching voltage and current conditions that should have posed no threat of failure. The paper was followed by others [2-8] and, in 1967, by a comprehensive review article [9] and bibliography [10]. While second breakdown is still a reliability problem in power transistors and metal oxide semiconductor field-effect transistors (MOSFETs), it is controlled through device design and the specification of safe operating areas that are based on the work reported in this paper. An important aspect of the paper it that it represents the genesis of NIST's support for the semiconductor industry. Work for that industry is now conducted throughout NIST; in particular, there is an Office of Microelectronics Programs and a Semiconductor Electronics Division.

This work was initiated in response to a request to the National Bureau of Standards from the standards arm of the Joint Electron Devices Engineering Councils (JEDEC), operating under the Electronics Industries Association. The reasons cited for their request were several. To achieve an adequate understanding of the mechanism would have required a long-term effort not likely to be undertaken by any individual member company. Nevertheless, it was needed by a large segment of the industry. The literature on second breakdown was slight and inconclusive. Finally, different, controversial opinions, in part due to company prejudices, were widespread. To assist NBS to conduct its research on second breakdown, member companies provided power transistors for testing, copies of reports of their experience, and access to their engineers and scientists concerned with this reliability problem.

In the paper *"Second Breakdown" in Transistors* [1], each of the mechanisms that had been proposed in the literature was examined and shown to be inadequate. A more complete description of the characteristics of second breakdown was given and it was shown that it is a fundamental property of the transistor. On the basis of an observed delay time before the initiation of the breakdown, it was proposed that the phenomenon is related to a thermal mechanism. It was shown that the onset of second breakdown cannot be predicted simply in terms of voltage and current, as had been the practice, but that it is important to characterize second breakdown in terms of the energy dissipated in the transistor, and further, that the energy threshold (or delay time) is dependent on other factors such as ambient temperature and the biasing base current of the transistor.

The conclusions in this paper provided the basis for all current methods to specify reliable operating limits of power transistors. These specifications are given in terms of safe areas of operation for collector current and voltage that are dependent on the biasing base current and the switching dynamics.

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July 1995 marked 40 years of NBS/NIST programs to support the semiconductor industry. Quoting a press release issued at the time, "The Commerce Department and the U.S. semiconductor industry next month [July 1995] will celebrate the 40th anniversary of a partnership in a field that has enabled such technological advances as the development of sophisticated diagnostic medical devices, laptop computers, and home bread-making machines. These advances have profited from the support the industry has received in the past 40 years through the semiconductor research program at the Commerce Department's National Institute of Standards and Technology."

These efforts began in July 1955, when electronics scientist Judson C. French was entrusted by NBS management with a budget of $10,000 and a mission to see what kind of support NBS could give to the growing transistor industry. French approached the American Society for Testing and Materials and the Electronic Industries Association to help define a need that NBS could fulfill. Each organization identified measurements critical to dealing with the great discrepancies in both manufacturing and product specifications that were still unresolved by member companies. So, armed with a project from each organization, NBS embarked on a new program of measurement research that would, decades later, inspire the Semiconductor Industry Association to note that "NIST is the only place in the U.S. where the broad range of measurements needed for semiconductor processing are routinely and systematically developed."

In the early 1970s, NBS was requested by the Defense Advanced Research Projects Agency to help the Defense Department develop integrated circuits with increased performance and reliability levels. Both military and private-sector organizations profited from the measurement improvements. In one case, the investigation of wire bonding of integrated circuits established new procedures, now implemented in commercially available equipment, that increased circuit yields by as much as 35-fold and made possible large military hybrid circuits that utilize more than 500 wire bonds each.

In 1981, Charles River Associates conducted studies to investigate the economic benefits provided by NBS work in semiconductor technology. These studies found that industry respondents received several benefits from the use of NBS results, including improved product reliability, increased production yields, increased ability to meet customer specifications, improved product features, cost reductions, and new directions of company research.

The report concludes that "the overall industry productivity level was approximately one percent higher for the years 1973 to 1977 [which were covered by the studies] than it would have been had the technical information acquired from NBS not been available" and that the median rate of return to the economy and society on investment in the NBS work was 140 percent per year. Later comparisons with industry data showed that NBS had provided four percent of the total industry productivity increase during the period.

Work spawned by reference [1] is profusely evident in industry. NIST's work on photomask linewidths led to a tenfold reduction of intercompany measurement discrepancies, stimulated the production of new instrumentation, extended the range of use of optical microscopes, and provided techniques and calibration standards that have been adopted industry-wide. All U.S. semiconductor device manufacturers use NIST measurement methods and standards. A study of the benefits of this work estimated a $30 million annual savings to the photomask producers alone.

NIST designed and built the world's most accurate ellipsometer to develop and issue standard reference materials for measurement of silicon dioxide layer thicknesses between 10 nm and 200 nm, measurements critical to industry for precise manufacturing control.

NIST stimulated the first marketplace use of integrated circuit test structures, which are devices formed on the wafer during manufacture that can be probed electrically to measure properties of materials, quality of processing steps, device operation, and mechanical properties. Test structures based on electrical measurements have been developed at NIST for measuring dimensions (so-called "critical dimensions"); overlay, a measure of registration between layers of a device; and electrical linewidth with uncertainties in the 10 nm range.

Results of NIST's methods of evaluating susceptibility to electromigration—which causes the interconnect metal on modern integrated circuits to fail—have been used by at least 14 companies. An independent study reported that benefits to this industry, including reduced production and transaction costs as well as improved research efficiencies, led to an estimated aggregate social rate of return of 117 %.

Harry A. Schafft began his NBS career in 1958 as an Electronics Engineer in the Semiconductor Electronics Division. In addition to his research on second breakdown in transistors, he started a program in 1982 to improve the characterization of interconnect metallizations for their resistance to electromigration. This work resulted in the development of three American Society for Testing and Materials (ASTM) standards and numerous journal publications. His recent work has focused on developing and coordinating techniques for building in the reliability of semiconductor devices by identifying and controlling critical process fabrication parameters. Other areas in which he has made contributions include photovoltaic electric power systems, measurement problems related to wire bonds, and measurement technology required by the cardiac pacemaker industry. He is a Fellow of the the Institute of Electrical and Electronics Engineers (IEEE) and received a Department of Commerce Bronze Medal in 1983 and a Silver Medal in 1992.

Judson C. French joined the National Bureau of Standards in 1948. He conducted and later directed research and development in microwave gas tubes and semiconductor materials and devices prior to his broader assignments in research management. He served as Chief, Electron Devices Section (1968-1973); Chief, Electronic Technology Division (1973-1978); Director, Center for Electronic and Electrical Engineering (1978-1991); and Director (1991-1999) and Director Emeritus (1999), Electronics and Electrical Engineering Laboratory. French has served as a member of the Optoelectronic Computing Systems Center Policy Board at the University of Colorado since 1992 and as an observing member of the Board of Directors of the National Electronics Manufacturing Initiative, Inc., since 1998. He has co-chaired the Joint Management Committee of the U.S.—Japan Joint Optoelectronics Project since 1992. He is a member of the National Academy of Engineering and a Fellow of the IEEE, and he has received Department of Commerce Silver and Gold Metals and the Edward Bennett Rosa Award of NBS. In 1980 he received the Presidential Rank of SES Meritorious Executive and, in 1984 and 1993, the rank of Distinguished Executive.

Prepared by Harry A. Schafft.

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