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Fundamental Research and Device Technology

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Abstract

Highlights of the interaction between fundamental research and semiconductor device technology are summarized.

1. Prehistoric times (i.e. BS-Before Shockley)

The first forty years of the twentieth century witnessed the discovery of quantum mechanics, the photon, electroluminescence, the role of defects in solids and the properties of metal-semiconductor contacts, all of which laid the foundation for the technological revolution that was to come. Quantum theory explained the difference between metals, semiconductors and insulators in terms of energy bandstructure, and accounted for electron states associated with lattice defects and impurities. In 1934 Fermi invented pseudopotentials, which were to become vital for bandstructure calculations. Schottky and Mott, separately described the metal-semiconductor contact in 1938, an understanding that was to become crucial to devices like MESFETs, MOSFETs, IMPATTs and charge coupled devices. Semiconductors began to be used as thyristors and photodetectors and point-contact rectification was beginning to be understood. And then there was Shockley...

2. History

Modern electronics began with the invention of the transistor at Bell Telephone Laboratories in Murray Hill, New Jersey by Bardeen, Brattain and Shockley who were subsequently awarded the Nobel Prize in 1956. (Since all of the elements in what follows can be found in most text books, the author will save space by not quoting detailed references.) The early transistors were chunky, centimetre-sized single crystals of Ge with p-n junctions back to back involving both electrons and holes. The physics of p-n junctions was set out in a classic paper by Shockley in 1949, the first example of what was to become a very fruitful interplay of physics and device technology. Shockley went on to contemplate the effect of heterojunctions (1951) and the advent of the junction field-effect transistor

(JFET) (1952), innovations that had to wait a number of years for crystal-growing techniques to catch up with theory. At present time, field-effect transistors based on Si have revolutionized electronics and heterojunctions based on GaAs have found extensive rôles in hot-electron transistors, photodetectors and, of course, in quantum-well devices.

Semiconductors became recognized as being extraordinarily versatile materials and new devices were quick to follow. Perfect marriages of quantum theory and semiconductor technology led to Esaki's tunnel diode 1958 (another Nobel Prizewinner, in 1973) and, after Townes's invention of the maser in 1954, to the semiconductor laser described by Dumke in 1952. A theoretical exploration of the effect of bandstructure on charge transport, initiated by Krömer (1958), lead to the discovery of negative differential resistance (NDR) and associated instabilities by Ridley and Watkins (1961, 1963). These effects in GaAs, predicted by Hilsum in 1962 and discovered by Gunn in 1963 triggered a range of transferred-electron devices (TED) that paralleled IMPATTs as microwave generators. GaAs, CdS and other III-V and II-VI compounds offered a further instability through their piezoelectricity giving rise to the acoustoelectric effect but devices based on this failed to materialise. Nevertheless, the piezoelectric effect was exploited in surface acoustic wave (SAW) devices.

A second revolution was seeded by Esaki and Tsui in 1970 through their idea of Bloch oscillations in a superlattice, but its fruition had to await the development of planar technology, particularly molecular-beam epitaxial growth. Since around 1980 the ability to precisely control the layer thickness down to atomic dimensions has encouraged a whole new family of devices, both electronic and optical, based on the quantum confinement of electrons in quasi-low-dimensional structures. This gave rise to the discovery of new effects, such as the real-space-transfer mechanism for NDR (Hess et al., 1979) and the quantum Hall effect. The quantum Hall effect discovered by von Klitzing (1980), for which he was awarded the Nobel Prize in 1985, has lead to a standard of resistance based purely on two fundamental constants ($h/e^2 = 25.805k\Omega$). The ability to fabricate mesoscopic structures (those with dimensions intermediate between microscopic elements, such as atoms, and macroscopic elements) has allowed the investigation of fundamental quantum transport (albeit at temperatures in the milikelvin range) in which the wavelike properties of the electron become observable in ballistic conductors. Quantized conduction and the Aharonov-Bohm effect have been observed and single electron effects (Coulomb blockade) have been seen in quantum dots. Nobody is sure yet whether any of this has any bearing on practical devices, though it is clear that as device dimensions shrink the standard classical drift-diffusion analysis pioneered by Shockley to describe transport is no longer adequate.

Another line of research bearing on large area electronics (LAE) was the investigation of amorphous semiconductors by Mott and others, particularly at Cambridge, for which, inter alia, Mott won the Nobel Prize in 1977. Apart from the current application to solar cells there is considerable promise for cheap and easily fabricated transistors based on amorphous semiconductors.

3. Processes

The development of semiconductor devices could not have proceeded coherently without the establishment of an understanding of the fundamental physical processes involved in their operation. Many scientists in many fields of semiconductor physics were involved in this activity a few being theoreticians, spectroscopists, crystal growers among many others, and to pick out a few names is somewhat invidious. The highlights picked out below are just those that reflect the author's personal bias and need not be thought of as in any way definitive.

Perhaps the most fundamental property of a semiconductor is its bandstructure. Using the so-called empirical pseudopotential method Philips and Cohen and their co-workers during the sixties calculated the bandstructures of Ge, Si and other semiconductors, which provided a firm basis on which to build other electronic properties. Chemical trends, illuminated by Phillips and van Vechten, provided a more global understanding of bandstructure than could be provided by the contemplation of individual numerical calculations.

Equally fundamental for the operation of electronic devices is charge transport which led to such questions as: what determines the mobility of carriers, their lifetime and the behaviour at high electric fields? Not surprisingly, given the state of early material, the effect of impurities and dislocations were tackled first. Rutherford scattering was adapted to describe charged-impurity scattering by Conwell and Weisskopf and by Brooks and Herring resulting in their well-known formulae, and Read described dislocation scattering. Shockley and Read gave an analysis of the lifetime of carriers excited by light and influenced by impurity states in the energy gap. But even in pristinely pure material there is still a source of resistance in the form of lattice vibrations. Bardeen and Shockley introduced the important concept of the deformation potential to describe acoustic phonon scattering and Shockley showed how this type of scattering led to non-ohmic behaviour at high electric fields. Later, Harrison extended the deformation potential idea to optical phonons, and Reik and Risken could then solve the Boltzmann equation and describe in detail hot-electron behaviour in Ge. As GaAs entered the fray it became necessary to account for polar scattering and, fortunately, this had already been done by Fröhlich for optical modes. Piezoelectric scattering was analysed by Meyer and Polder at the Philips Laboratory in Eindhoven. An important criterion in any electronic device is its breakdown field and the description of breakdown via impact ionization occupied a number of theorists (and still does). Shockley's idea that impact ionization was due to lucky electrons, that is those that escaped all collisions, was shown not to be viable by the numerical work of Kane and Baraff and it was only many years later that it was shown by Ridley that the essential feature was the lucky-drift electron, one that suffered momentum-relaxation without appreciable energy relaxation. If the problem of breakdown was solved for small-and moderate-bandgap semiconductors it has reemerged for large-bandgap materials like AlN, GaN and ZnS.

There are many other topics worth mentioning- - -deep-level impurities, growth mechanisms, thermoelectric effects, non-linear electronic and optoelectronic effects, organic semiconductors among many, many others, space forbids further exposition. It is nevertheles clear that the whole field exhibits relation between fundamental physics and device technology.

4. The future

Predicting activity in the field of semiconductor physics and technology in the near future is relatively safe so I conclude with the following list of areas and fruits they might bare, in no particular order:

1. Large-bandgap semiconductors for high-power devices and visible lasers;
2. Amorphous semiconductors for large area electronics;
3. Organic semiconductors;
4. Exploitation of quantum phenomena in quantum computing;
5. Quantum devices;
6. Molecular engineering for smaller, faster devices.

The show is set to run and run!