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Invited

The Materials Challenge

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Integration of electronic and optical functions into the three-dimensional scaffolding of perfected single crystals has elevated materials science into a position of primary importance for the development and realization of novel devices. The tremendous success of silicon technology is, however, not easily copied for more complicated materials, such as semiconductor compounds, cuprate superconductors, liquids, or ceramics. Basic materials science, atomic control of epitaxial methods, mastering of sophisticated interfaces, and refined and theoretically supported analysis provide the exciting challenges for the future.

"Solid State Devices *and* Materials" , the very name of our Conference accentuates the intimate relation between devices and their realization through materials control. The invention of a new device principle or its simulation on a computer create much exciting intellectual activity, but the harsh reality in a pilot line or the final verdict over profit or loss in an electronics production fab is delivered by materials and their processing.

The field effect transistor represents a most dramatic proof in case. Its principle was proposed very early, long before the realization of the point contact transistor in 1947. Yet it took an inordinately long time and tremendous efforts to sufficiently purify the silicon dioxide, also its underlying silicon and - especially - the vital interface between semiconductor and dielectric to achieve acceptable channel mobilities and to reduce to practice the principle of the field effect transistor. I remember this time, when I closely observed my friends and laboratory neighbours at the Bell Laboratories performing this laborious task. Then a statement made the rounds: " *The materials man's most important problem is materials, but the device engineer's most important problem is ... materials!"* Much of this quotation still holds true today; device development must take materials specifications into consideration from the very beginning. The most successful device groups are usually the ones with closest contacts to good materials groups. This tendency will intensify, even against the obstacle of ever increasing complexity and cost of scientifically handling semiconductors, dielectrics, fibers, or optical and magnetic materials.

These remarks sound trivial today; we are all aware of this link between the science of materials and the industrial reality of devices. This vital part of materials science is, however, a quite recently acquired approach. The short time since the Fifties of our century - with the new stringency of high-purity semiconductors arising and succeeding - contrasts drastically with centuries of earlier attitudes. Materials were admittedly considered to be important, otherwise humankind would not have accepted the naming of the great epochs of civilization after materials: the stone age, bronze age, and - now just terminating - the iron age. These materials were initially just found lying around; the art of creating wooden tools or stone implements consisted not in willfully creating these substances but in finding, selecting, and eventually shaping and combining them into useful gear. The advents of smelting ore into bronze and producing iron and steel alloys were major steps forward, yet even these materials were utilized in macroscopic bulk form, then shaped and connected into systems. The functionality is here not so much given by the atomic properties of the material but in the artistry of shaping and connecting. The goldsmith by far exceeded his materials supplier in importance and status.

Materials actually played an inferior part in the establishment of modern physics. Quantum theory was experimentally established with the materials-free black-body cavity, not accidentally but by clever design to avoid all unreliable and irreproducible solid light-emitters. The vacuum was also a more important medium for atomic and electron physics than any material! These historical reminiscences are necessary to fully appreciate today's techniques of generating and applying complex materials with precise control down to single atoms, with the functions integrated inside the atomic arrangement of the solid and no longer based on external joints!

This remarkable development is not universally feasible, but at present restricted to very few highly controlled substances, especially the elemental and some compound semiconductors, quartz and related dielectrics. One of our future challenges will be to extend these achievements of purity and crystal perfection to other classes of materials. At present, however, the trends are towards still higher perfection of those few already highly domesticated materials; the overwhelming dominance of silicon, especially in the MOS-technology, provides both the impetus and the rewards for the tremendous expenses involved. A self-supporting monopoly has arisen; ours is indeed the epoch of the silicon age.

The compounds, led by GaAs and InP and even now followed by $A^{II}B^{VI}$ semiconductors, however, stay in the race, as our Conference demonstrates. It is the epitaxy technology, with atomic precision, in-situ controls, and the variability of alloying and mixing to control band structure that keeps them as viable contenders against silicon with its excessive purity and easy dopability.

Interfaces have been the first crucial challenges in this new era of materials: Ferdinand Braun's point contacts, Schottky's metal contacts, and Bell Laboratories' germanium p-n junctions. Interfaces will remain the essential challenges. It is here where electrical and chemical potentials change most rapidly; electronic functions are created by adjoining surfaces of distinctly differing substances. Fermi's alleged dictum: " *surfaces are nice, but there is so little of them*" misses the point. A surface certainly has only $N^{2/3}$ atoms, which is small compared with N^3 in the bulk. Nowadays, however, with reduced dimensionalities and consequently a shrinking N, the outlook has changed - it is the interfaces where functionalities arise, and not the bulk anymore as it used to be in bronze and iron ages!

Characterization of materials prior to further processing has always been an essential prerequisite, but today has become indispensable for modern electronics. The advent of novel methods with resolutions down to individual atoms has already changed technology, further accelerating miniaturization trends but also raising the standards of expectation for the quality of materials, their interfaces and built-in structures. This demand in turn calls for high-resolution methods to control and continually monitor the evolution of structured materials during each step: in-situ, contactless methods are needed. The tremendous success of molecular beam epitaxy with exactly this set of tools for in-situ analysis has stimulated efforts on this front, which will become even stronger in the future, in spite of their sophistication. complexity, and cost.

Attention to atomic detail in materials will be our challenge for the coming decades, which is a major step ahead from earlier polycrystalline or amorphous bulk materials, where average, macroscopic quantities sufficed for usage in composite structures. The integration of functions into minimal crystal dimensions is a stupendous task, but this task can be solved by a coordinated interplay of the arts of materials-making with the fundamental sciences of solid-state physics and chemistry in order to realize the ideas of the device designers.

Diverse, subjectively selected examples illustrate our contemporary materials challenge in this presentation. Impurities and lattice defects in silicon and their electronic properties can be ascertained with extraordinary sensitivity; liquid-phase epitaxy and anodic etching create novel varieties of silicon. Compound semiconductor heterostructures constitute particularly fascinating assignments, whose difficulties grow with increasing ionicity of the atomic bonds. The cuprate superconductors seem to inherently resist all attempts towards crystalline perfection. Many newly invented characterization methods with high spatial and temporal resolutions, and often non-invasive, will become essential for monitoring materials preparation, processing, and clarifying device operation and reliabilities.

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