DESIGN OF INTELLIGENT MATERIALS FOR FUTURE ELECTRONICS

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ABSTRACT

With increasing a demand for higher speed and performance of a computer, a new concept of electron devices is indispensable for the future electronics. Devices with intelligent materials meet such a demand and can simplify electronics, so that a system made of the devices can perform more complex functions as close as those for human brains and organisms. Intelligent materials are distinct from conventional materials in their characteristics, and they have high potential to become a dominant electronic material in the future because of their various built-in functions. In this paper an important concept in the design of intelligent materials, called k-space engineering, is also introduced, and the k-space engineering, which manipulates the band structure of an existing material, is promising for the future electron devices.

INTRODUCTION

Continuous advancements in technology have resulted in integrated circuits with a smaller device dimension and greater complexity. The silicon (Si) very large scale integration (VLSI) technology opened a new electronics era and established the computer age in the 20th century. Emergence of a computer has improved human life to a great extent. A demand for higher speed and performance of a computer escalates with time and drives the Si VLSI technology to the Si ultra large scale integration (ULSI) technology. The dimension of metal-oxide-semiconductor field-effect transistors (MOSFETs) becomes smaller with increasing an integration level in the Si VLSI and is expected to be 0.1 μm in giga-bit dynamic random access memories (DRAMs), which will possibly appear in the latter half of the 1990's.[1]

The Si VLSI technology is, however, about to approach fundamental limits in manufacturing process, device physics and interconnections. One example of the limits in the manufacturing process is lithography. As long as light is used, the dimension of lithography will be eventually limited by the light wavelength, and other lithography techniques such as X-ray and electron beam must be used for 0.1-μm MOSFETs. These techniques are, however, not suitable for volume production. In scaled-down MOSFETs, several physical problems rise: dielectric breakdown, hot carriers and short-channel effect. They affect the device reliability.

Can we still overcome the above limits and accomplish the ULSI technology? An answer is "yes" or "no." We will accomplish the ULSI technology for giga-bit DRAMs with hard work and intensive research but will again face the fundamental problems if a demand for higher integration is endless, which is human nature. Then, unless we tackle the problems in a different way, we will not be able to further improve the computer performance. We are approaching a turning point from the 20th-century to the 21st-century electronics and must establish a new concept for design of the 21st-century electron devices now.

FUTURE ELECTRONICS

In the future electronics, an integrated circuit of transistors with a single function performs multifunctions with an aid of circuit and software design. When a complex function is required, the circuit and software design becomes extremely complex. There is a limit for complexity of a function to perform even with a complicated circuit and software design. For instance, synthesis of a human brain using integrated circuits requires great complexity in the circuit and software design, and even if it is made, the artificial brain may not be capable of all functions of a human brain. A circuit component, that is a transistor, should have more built-in flexibility in order to unload the burden from the circuit and software design.

In future, a device with multifunctions is expected to perform various functions without much relying on the circuit and software design, and the electronics should be simple enough to afford more complex functions with a sophisticated circuit and software design. Materials and devices with high flexibility are inevitably in great demand. With the use of materials whose properties are modifiable with external stimuli, careful selection of materials meeting requirements for electron devices will be no longer necessary. One material does all functions: conductor and insulator, for instance. Such materials are "intelligent" because they are adaptable to human needs, and we can modify their properties or characteristics as the need arises. A device with intelligent materials also can have characteristics modifiable with external stimuli. Such a device is "adaptive." An integrated circuit made of adaptive devices possesses multifunctions without much relying on the circuit and software design and performs complex functions as close as those for human brains and organisms with an elaborated circuit and software design.

The movement from "structural" to "functional" materials will be extended to "intelligent materials" as we move into the future.

INTELLIGENT MATERIALS IN FUTURE ELECTRONICS

What distinguish intelligent materials from conventional materials are the functions as follows: environment-judge/adjust function, self-restorative function, self-diagnostic function, and time-dependent function.

The ability to judge and adjust to the environment is not completely absent from conventional materials, and many devices have been developed based on this function. The temperature sensors referred to as thermistors are an excellent example. Thermistors are based on a material whose resistance increases as the temperature changes-a material which can be said to incorporate the ability to judge and adjust to the environment.

The pattern, however, will move to one where materials such as biological materials will possess the ability not only "sense" the environment and change in response to a change in the environment but also to restore themselves. Such materials should be able to repair themselves when broken or modified, or even to diagnose potential problems and generate a warning before a difficulty occurs. This function could be referred as "self-diagnostic".

In addition, there will be efforts to use materials whose particular characteristics are programmed to change over time. Such materials may grow or even multiply. We can refer to this function as a "time-axial function", analogous to the "metabolic" functioning of biological materials.

Indeed, the organic materials that constitute living organisms ("biomaterials") possess the full range of these functions. Biomaterials, in fact, would seem to be synonymous with what we think of as intelligent materials.

As we move into the future, however, it will become possible to plan and control the physical, functional, chemical, and other basic values of the materials we develop. This control will allow us to create intelligent materials.

There are two ways to realize intelligent materials. One is to synthesize intelligent materials from nothing by arrangement of various atoms, and the other to metamorphose existing materials into intelligent materials.

Advanced epitaxial technology in semiconductors is now available to deposit high-quality multi-layered structures such as superlattices, which were originally proposed by Esaki and Tsu.[2] The epitaxial technology along with the ultra-fine lithography technology using electron beams can create the low dimensional structures. The low dimensionality metamorphoses existing materials into intelligent materials as further discussed later.

A recent progress in scanning tunneling microscopy (STM)[3] demonstrated surface modification on an atomic scale, and it might not be a dream for an STM to be used to manipulate individual atoms in the near future. Various atoms can be arranged to synthesize intelligent materials using such an atom manipulator, as schematically shown in Fig. 1.

In either way, intelligent materials could be created. There is, however, an important point to consider in creating intelligent materials; that is an energy band structure of the material. We must know what the energy band structure should be to meet requirements for intelligent materials. Here, we introduce an important concept in the design of intelligent materials, called k-space engineering,[4] which will be discussed in detail next.

K-SPACE ENGINEERING

In solid state physics, material properties are well reflected by the energy-band structure in the k-space (momentum-space). The band structures of two most popular semiconductors, Si and GaAs, are shown in Fig. 2. The details of the nomenclature, L, Γ, X and K, are explained in any text book of semiconductor and solid state physics. The energy band filled with electrons and the empty band immediately above it are called the valence and conduction bands, respectively. The crystals in which both the conduction and valence band extrema occur at the same k value (e.g., at Γ) are called direct gap materials, as represented by GaAs, and those for which this is not so are called indirect gap materials, as represented by Si. Direct gap materials, in general, are more suitable for photonic devices because excitation or recombination does not require a large change in the k value.

The above is one example to show how well the energy band structure in the k-space is related to material properties. Therefore, by manipulation of the band

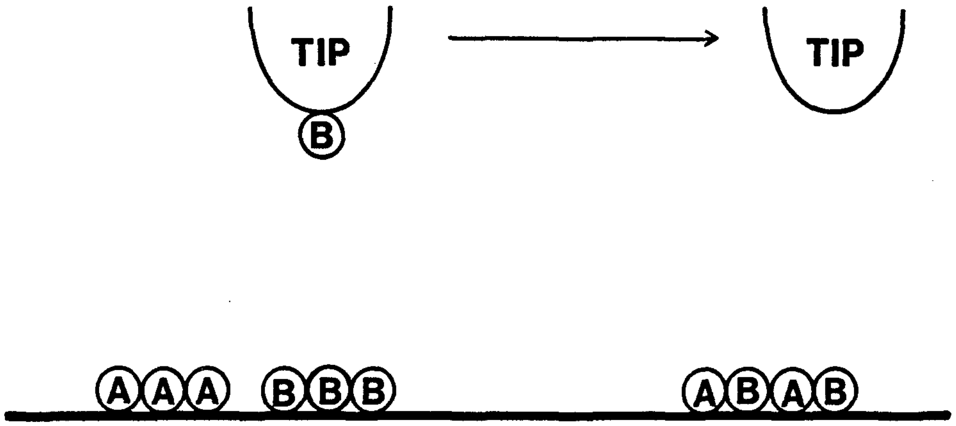
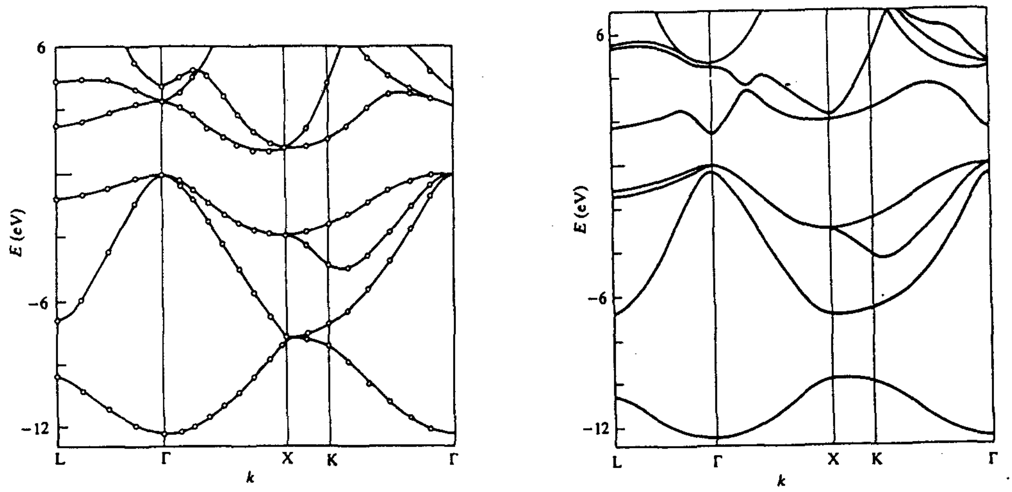


Fig. 1 Synthesis of intelligent materials by atomic arrangements using an STM.



(a)

(b)

Fig. 2 Energy band structures of Si (a) and GaAs (b).

structure, which we call the k-space engineering, we can modify the material properties.

A natural question to be asked is what stimuli can effectively modify the band structure. It is well known from recent extensive studies on semiconductor heterostructures that low-dimensionality and strain greatly influence the band structure. The low-dimensional materials such as quantum wells (2D), wires (1D) and boxes (0D) are found to show optical/electrical properties different from bulk material. The strain induced by a mismatch of the lattice constants of two materials in the heterostructure splits the heavy-hole and light- hole bands and modifies the band gap energy.

These two are some stimuli which effectively affect the band structure. However, they cause a permanent change in the band structure and are not removable once they are incorporated in a device. For ideal k-space engineering, the external stimuli to modify the band structure which can be easily applied and removed have to be found. Discovery of such stimuli gives a birth to real intelligent materials. Figure 3 shows an example of the use of such stimuli. External stimuli which effectively modulates the bandgap locally reduces the bandgap of a wide-gap semiconductor. This could be a simple way to fabricate quantum boxes.

Although we discussed direct modification of the band structure using the k-space engineering, there is another form of the k-space engineering. The present electron devices are operated in the real space, but the performance could be optimized if they were controlled in the k-space. Another form of the k-space engineering is to design a device whose performance is optimized based on the energy band structure of materials and effectively utilize materials.

For example, electrons are scattered to the satellite valleys, X and L valleys, from the Γ valley in Fig. 2 in the high electric-field region of an AlGaAs/GaAs heterojunction bipolar transistor (HBT) and lose speed, which limits the performance of a high speed HBT.[5] However, if the k values of electrons in the transport process are controlled by some means, maybe by localized electric/magnetic fields or by selecting a channel direction so that the electron scattering to the satellite valleys will be unlikely in the k-space, the performance of the HBT will be optimized.

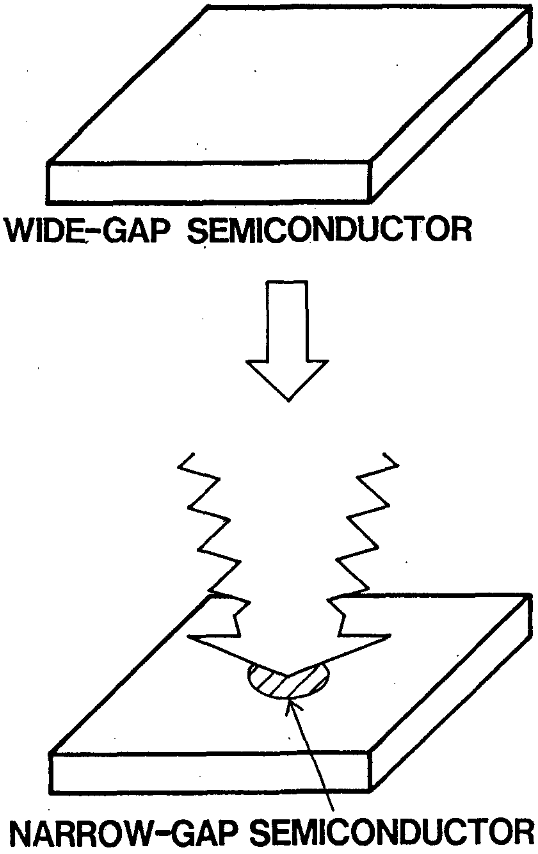


Fig. 3 Energy-band-structure modulation (k-space engineering) by localized stimuli.

CONCLUSIONS

In the future electronics, there will be a great demand for materials and devices with high flexibility. A device with intelligent materials meets such a demand. The properties of intelligent materials are modifiable with external stimuli, and a device with intelligent materials is adaptive.

Although an ultimate goal is to synthesize intelligent materials by arrangements of various atoms, it may not be accomplished in the near future. A more practical approach is to metamorphose existing materials into intelligent materials, based on k-space engineering, which manipulates the band structure of existing materials depicted in the k-space, is a unique way to modify material properties. Once the external stimuli to affect the band structure which can be easily applied and removed are found, the k-space engineering will become a high potential technology for the 21st-century electron devices with intelligent materials.

Most concepts on the future electronics presented here are based on the view of a scientist with expertise on semiconductors, and materials other than semiconductors may play an important role in the future electronics. Particularly the concept of k-space engineering could be more feasible with the use of conductive polymers, which have higher flexibility in the structure than "rigid" semiconductors.

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