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April 1987

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General Description of a Semiconductor Superlattice

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(April 1987)

ABSTRACT

A qualitative description of the physics of a semiconductor superlattice is presented in relation to chemistry. A section of this paper is devoted to semiconductor superlattice construction to underscore the salient characteristics of electrical conductivity, photoluminescence and optical enhancement for elements in Groups III-VI of the periodic table.

Introduction

The purpose of this paper is to provide an introductory description of the structure of a semiconductor superlattice for the non-expert with a chemical background. There is a demand for the use of a semiconductor superlattice for device applications, and with the demand a need to appreciate the concomitant complex chemical and engineering aspects of these materials. A semiconductor superlattice is composed of semiconductor layers of alternating composition. A semiconductor exhibits increased electrical conductivity with an increase in temperature, while thermal conductivity decreases with an increase in temperature. In metals both electrical and thermal conductivities decrease with an increase in temperature. The interaction between the superlattice layers determines both the type of semiconductor characteristic and the degree to which the characteristic is manifest. The fields of chemistry, physics and engineering provide the necessary background in order to predict the chemical interactions of these multicomponent layers prior to construction.

The paper is divided into four sections. The first portion deals with the history of the word superlattice in 1914 and how the definition differs from what we mean today. The second and third parts are devoted to descriptions of the semiconductor and semiconductor superlattice, respectively. The last section provides a step-wise construction of a semiconductor superlattice, and a demonstration of how materials can be altered to produce enhanced properties.

History of the Superlattice

The word superlattice has been used to describe two different types of structures in the past seventy years. In 1914 Kumakov, *et al.*¹ discussed the structure of Cu_3Au and used the word "superlattice", taken from the German, *überstrukt*, which means "above structure". In this case, superlattice refers to a structure formed by annealing the sample such that the copper atoms reside in one layer and the gold atoms reside in another layer exclusively, and that these layers are superimposed on one another. On the other hand, superlattice described in terms of a semiconductor depends on an energy difference between potential wells resulting from compositional layers and not exclusively upon the purity of the layers. The distinction between these two definitions is being made at this point in the paper for two reasons. The most important reason is not only to clarify terminology but to encourage

the reader to carefully examine the meaning of specific phenomena in context as well as for the general scientific implications. Second, the physical separation of this section should avoid the confusion of coupling the word superlattice as it applies to the crystal structure of Cu_3Au with the description of a superlattice as it pertains to the semiconductor industry.

In 1935 Sykes and Evans² utilized the term superlattice to describe the structure of Cu_3Au . This Cu_3Au superlattice is a spatial arrangement of atoms such that only one type of atom exists per layer, and that alternating copper and gold layers are superimposed on one another. Pictured below is a three-dimensional model of Cu_3Au .

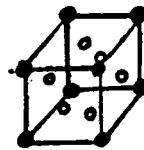


Fig. 1 Cu_3Au spatial representation

The open circles represent the copper atoms and the closed circles the gold atoms. There are six faces per cube. The atom represented by the open circle at the center of a face is shared by two faces or cells so that there are three face-centered copper atoms/unit cell. Consider the atom represented by the solid circle at the corner of the cube. There are eight vertices per cube and one atom at a corner which is shared by eight intersecting cubes, therefore the ratio is one atom/unit cell. The ordered Cu_3Au structure has copper face-centered atoms and gold atoms at the vertices for each layer in the three-dimensional structure. This ordered structure is characterized by low resistivity and corresponding high conductivity values.³

If a copper-gold mixture is cooled slowly, the ordered structure just described is obtained. If the mixture is quenched, however, a random or disordered structure is formed because the copper and gold atoms do not equilibrate to reach the preferred face-centered or corner sites. Annealing Cu_3Au allows time for diffusion of the copper and gold atoms to form the thermodynamically preferred layered structure. The ordered structure of Cu_3Au forms a superlattice; however, when quenched the three-dimensional ordered structure is not allowed time to form and there is discontinuity in conductivity.⁴

The Sykes and Evans Cu_3Au superlattice is provided as an example to show the evolution in meaning of the word superlattice. Superlattice can be used on the atomic scale as described by Sykes and Evans, or for multiatomic layers as it is currently used to describe a semiconductor superlattice.

Semiconductor Description

At 0 K a semiconductor behaves like an insulator, and conductivity increases with increasing temperature so that the semiconductor becomes an intermediate electrical conductor. Typical semiconductor characteristics include electrical resistivity values of 10^{-2} to 10^9 ohm-cm at room temperature, and enhanced electrical conductivity, photoluminescence and optical properties greater than those properties demonstrated by insulating materials.⁵ These characteristics emerge with thermal agitation, or in the presence of impurities and/or lattice defects. Man has manipulated and enhanced the electronic contribution found in nature. How does this happen?

A pure crystal of silicon at 0 K is an insulator because the electrons are not free to move. Electrons are the charge carriers for electrical conduction only when they reside in energy states of the conduction band (see Fig. 2). The word valence is thought of in terms of chemical bonding. Outer-shell electrons, valence electrons, are the ones which form chemical bonds. The electrons are promoted from the valence band to the conduction band in a semiconductor when the crystal absorbs a photon. This quantum of light provides enough energy to promote an electron over the bandgap to the bottom of the conduction band in the semiconductor. The return of this electron to the valence band is described by electron recombination. The band gap is the energy difference between the conduction and valence bands.

The Pauli Exclusion Principle provides an explanation for electron occupation of a band for both metal and semiconductor, for what appears to be two different models. The Pauli Principle states that each level in the conduction band can accept at most two electrons of opposite spin, whether the material is a metal or a semiconductor. The difference between the structure of a metal and a semiconductor is due to the energy gap of their respective valence and conduction bands. There is no band gap in the metal. In the semiconductor not only is there an appreciable band gap, but the valence and conduction bands are divided into substates to form two continua. The difference between the physical

arrangement of the bands in the metal and the semiconductor does not change the fact that there are still the same number of energy levels available to the electron. These energy levels are simply arranged in a different way. It is the nature of this arrangement will be discussed below.

In a simple metal there are fewer electrons than positions available in the valence band, whereas the valence band is full in the semiconductor. In a semiconductor the electrons are concentrated between the atoms. In a metal the electrons are delocalized and spread out like an electron gas. This means that at low temperatures a metal is a better electrical conductor than a semiconductor, and that as the temperature is increased in the metal, the vibrational component between the atoms increases which results in decreased conductivity for the metal. Electron promotion is the process by which an electron is promoted from the valence to the conduction band for a period of time. The electron travels over an energy bandgap (E_g) distance. The width of the bandgap is critical, as the width itself often determines how many electrons will be promoted to the conduction band. The electron's promotion is measured in terms of speed and residence time, both of which are a consequence of the interaction of energy levels. Electron promotion, especially in relation to bandgap distance, will be treated more fully in the next section with the discussion of the semiconductor superlattice. Examples of semiconductors coupled with pertinent chemical parameters will be described in the balance of this section.

Common semiconductors include silicon, germanium, selenium, cuprous oxide, lead telluride, lead sulfide, silicon carbide and gallium arsenide. Table I lists common factors of these elements. Several conclusions can be drawn from Table I.⁶ Metallic behaviour of groups I-IV of transition elements relates to crystal structures with a high coordination number, 12 in the closest-packed lattice and 8 in the body-centered cubic lattice. Non-metallic members (groups IV-VIII) are covalently bonded and have low coordination numbers.⁷ For each non-metallic element, there are four or more s and p valence electrons. The semiconductors listed have crystal structures which can be three-dimensional networks, infinite layer lattices or long-chain molecules, with small coordination numbers. The measure of conductivity is often the measure of available electrons for promotion. It is understood that ionization energy is the minimum energy required to remove an electron from a gaseous atom to make a gaseous ion. In practice, an electron enters each orbital to produce a half-filled set of orbitals which all have the

same spin. Recognition of crystal structure and specific bonding considerations, such as electron availability and the energy required for promotion, allow prediction of suitable semiconductor candidates.

The common semiconductors listed have had practical applications since the 1940's when the germanium rectifying diode and bipolar transistor were invented.⁸ In the early 1950's researchers preferred to work with gallium arsenide (GaAs) because of the many interesting reactions which occurred within it, and because the results could be compared to the existing work on germanium.

Gallium arsenide is used as a light-emitting diode (LED), injection laser, transistor, and as a source for high-frequency microwaves. These applications are possible because of the direct band gap optical transition, the enhanced electron mobility and large band gap over that found in either silicon or germanium alone, and because of the hot electron phenomenon. The hot electron phenomenon will be described below; optical transition will be discussed in terms of the lasing ability of GaAs in the next section. Consider the implications of these uses for GaAs.⁹

An injection laser made with GaAs measures 0.25 mm in length and reflectivity is provided not from high-reflectivity end mirrors attached to the laser, but from the refractive index which exists between air and GaAs. The high-frequency microwave application is the result of the Gunn oscillation which occurs when a hot electron relocates from a lower portion to a higher portion of the conduction band. This transition is characterized by lower electron mobility which produces negative resistance. This negative resistance causes current decreases as the electric field increases, which results in an instability expressed as an oscillation at an electrode. These voltage and current changes are found in the microwave range for GaAs and are known as Gunn oscillations.¹⁰

Up to this point the emphasis has been on a simple one-phase semiconductor which results from electron promotion in terms of the bandgap. This bandgap is a measure of energy and it will be discussed in greater detail in the next section. Although there are important applications for the simple semiconductor, the semiconductor superlattice is more versatile. A semiconductor superlattice is composed of two different semiconductors (or phases), consisting of from three to five elements and characterized by a sophisticated band-gap potential-well interaction.

Semiconductor Superlattice Description

A semiconductor superlattice is composed of interleaved semiconductor layers, each 4-10 nanometers thick.⁵ Conductivity can be several hundred times greater in the superlattice than observed for a simple semiconductor because more electrons can be promoted to the conduction band for a longer period of time. Electron residence in the conduction band is an important measure of the quality of semiconductor behavior. The two types of semiconductor superlattice are the compositional variety and the doped variant, which is a modification of the former. Figs. 3 and 4 will be introduced to illustrate the text in regards to the interaction of two semiconductors, their band gaps and the potential wells created.¹¹

The compositional or heterostructural superlattice is a periodic array of ultrathin layers of two different semiconductors in alternating patterns, each layer no more than a few hundred atoms thick. The band gap width is a decisive factor for a given semiconductor because when two semiconductors are chosen to form a superlattice, the potential well produced from the interaction of two band gap widths create a greater probability for electron residency in the conduction band. Additional low energy states are made available to the electrons in the conduction band. Refer to the diagram of the compositional superlattice, Fig. 3.

The diagram of the compositional superlattice illustrates the interaction of two semiconductors to produce a potential well. It is this well which gives rise to increased promoted electron lifetime. Promotion is characterized not only by a greater number of electrons being promoted to the conduction band, but by the fact that such electrons can travel to higher energy levels in the conduction band and reside longer than anticipated for the simple semiconductor. The reason for this increased residence time is the result of a smaller energy band gap. As evidenced by Fig. 3, the overall band width of a superlattice is determined by the strength of the interaction between neighboring potential wells. This interaction increases with the decreasing width of the semiconductor layer whose band gap is greater. The nature of the chemical bond for carbon, silicon and germanium will be reviewed in an attempt to appreciate the importance of the band gap distance.

Carbon, silicon and germanium belong to the same family in the periodic table. They can each have the same diamond structure, and yet the nature of the bonding itself is different for each element (see Table II). The energy gap for germanium is small (0.744 eV), and the electrons loosely bound. The reason for this is that as one goes down a family in the Table, the atomic size increases so that it takes less energy to remove an electron because the electrons are farther away from the nucleus. This trend is exemplified by carbon, silicon and germanium where it takes less energy to remove an electron from germanium, for example, than it would for carbon. This qualitative picture shows that there are more conducting electrons available for germanium because the energy gap is smaller. It is interesting to note that at room temperature germanium has a specific resistance of 50 ohm-cm and that as temperature is increased the number of electrons available increases. These electrons enter empty conduction bands, which results in a sharp decrease in resistance.

Consider Fig. 3, the diagram of the compositional superlattice. This diagram is divided into three major areas, *e.g.*, the energy band gap, and the conduction and valence bands. The bands are divided into continua, *e.g.*, minibands separated by minigaps. An electron must jump these energy minigaps in order to reside in the higher energy states of the conduction band. In the simple semiconductor the electron resides in the lowermost portion of the conduction band. In the semiconductor superlattice, the electron can travel to a higher level in the conduction band because of the strength of the interaction between neighboring potential wells which results from the interaction of the energy levels from two semiconductors. Basically, the continuum formed in the conduction band produces a high electron field which makes it possible for electrons not only to reside at higher levels in the conduction band, but to reside there for longer periods of time. This can be explained in terms of the Bloch Oscillator.

The Bloch oscillation is the result of the high electric field produced by the semiconductor superlattice which tilts the bands in the continuum. The slope of this tilt (the change of energy, E varies with the wavevector, k) is expressed by the charge on the electron multiplied by the voltage applied to the crystal, divided by the length of the crystal. This means that the slope increases with increasing voltage. Refer to Fig. 4. In the frame labelled (a) the electron is propelled towards the upper edge of a miniconduction band but falls short because the electron emits a phonon which excites thermal vibration in the

crystal lattice. This means that the electron falls to a lower energy level. Frames labelled (b) and (c) depict a semiconductor superlattice. The conduction miniband in these frames is not as broad as that pictured for the typical semiconductor. Additional energy levels are possible for the semiconductor superlattice because the energy levels are composed of two semiconductors which provide greater possibility for electron residence as a result of the tilt produced from the interaction between these energy levels. The superlattice configuration allows the electron not only to reach high levels in the conduction band, but to reside there longer. The conduction band is divided into minibands and minigaps, and the tilt of the conduction band allows a decrease in current and an increase in voltage. A high electric field produces the tilt. Frame (c) illustrates this phenomenon in detail. The act of emission moves the electron's center-of-mass a certain distance, Δz , which increases with increasing tilt. Thus, an increase in voltage has the curious effect of decreasing the current that flows through the crystal (semiconductor superlattice) which allows the electron increased residence in the conduction band. Constant current flow results from a positive resistance. The negative resistance just described leads to instability expressed as an oscillation in the applied dc field. This negative resistance is an example of the Gunn effect previously described, the primary difference is that this crystal requires a few volts to produce an oscillating current, whereas a typical Gunn effect requires several thousand volts.¹² Judicious semiconductor choice produces a superlattice which exhibits negative resistance, and which reacts instantaneously to voltage. Such a superlattice could potentially serve as an active element for an electromagnetic wave generator, with microwave radiation of wavelengths less than 1 mm (the microwave range is routinely accepted to be 1 mm to 10 cm).

The compositional superlattice is characterized by a more complicated bandgap configuration than that of the simple semiconductor. However, the drawback to the compositional superlattice is that the electrons, the charge-carriers, are promoted to the conduction band only as long as the crystal absorbs light. The doped variant of the compositional superlattice overcomes this limitation of crystal excitation by making holes and electrons not originally found in the compositional superlattice.

The doped superlattice is called the n,p-type.⁵ A permanent population of electrons and holes are produced by doping the respective semiconductors of the superlattice with impurities. Atoms are

selected with valence electrons which are one greater or less than the atom for which they substitute in the host crystal. If the dopant has more valence electrons it is called the n-type. The 'n' represents the electron-donating or negative charge. These extra electrons are readily released in the crystal. To produce a hole in the alternate semiconductor, the host material is doped with acceptor atoms; this p-type semiconductor provides positively charged holes. It is possible to take advantage of the fact that the semiconductor superlattice is composed of two semiconductors; one semiconductor acts as the host for the additional electrons, while the other semiconductor is the host for the additional holes. The advantage of doping a semiconductor superlattice is that a semiconductor is not an insulator, and the valence band area must accommodate not only the original electrons of the semiconductor but the added impurity atoms as well. The additional electrons induce a self-promotion of the electrons to the conduction band at 0 K. The drawback to this scheme is that not only do the donors and acceptors provide charge carriers for the superlattice, they also reduce the mobility of these carriers because the donors become ions which produce an electrostatic field. This field impedes the motion of the charge carriers by scattering them.

Scattering charge carriers can be minimized by confining the donors to the large band gap to provide spatial separation for the electrons from the donors, as electrons seek available states that have the lowest energy level in the conduction band. The degree and quality of electron promotion increases conductivity. In fact, conductivity for this n,p-type semiconductor superlattice is several hundred times greater than one would expect for an ordinary semiconductor with the same concentration of carriers. Basically, the components of the semiconductors have been rearranged in the superlattice to make more of a good thing. The n,p-type superlattice is especially useful for the fast electronic devices.

The semiconductor choice and bandgap are different for the doped variant, than for those of the compositional superlattice. The choice of semiconductors for a strict compositional superlattice requires that the interatomic distances approximately match. In the doped variant, the semiconductor can be the host material provided that both n- and p-doping are possible. In addition, the effective bandgap of a doped superlattice can be given a value from zero to the actual value of the gap of the undoped host material; this is accomplished by carefully choosing the appropriate combination of doping concentration

and layer thickness. A semimetal with a bandgap of zero and a residual concentration of free electrons is produced when the semiconductors are chosen to close the bandgap width. An example of such a superlattice is InAs:GaSb.

A direct bandgap is characterized by the fact that there is no momentum change when an electron makes a transition between the conduction and valence bands. In other words, the valence band maximum is directly under the conduction band minimum. Essentially, electron promotion can occur at the surface of a semiconductor in the presence of sunlight, rather than at the typical n,p-junction site beneath the surface. Gallium arsenide exhibits a strong, direct band gap which accounts for the lasing ability of GaAs. However, in the presence of sunlight GaAs is not a typical n,p-junction device and therefore not a good candidate for a solar energy device.¹³ The drawback of surface recombination of electron hole pairs in GaAs is that because of the band-to-band optical transition, photons do not penetrate either beneath the surface of GaAs or to the alloy GaAlAs, the alternate semiconductor in this superlattice. The result is that GaAs:GaAlAs with sunlight-induced topical (surface) recombination does not contribute to the electrical output at an n,p junction, and therefore this semiconductor superlattice cannot be used as a solar cell device.

Hovell¹⁴ devised a scheme to overcome the topical recombination of GaAs and hence to produce a different type of semiconductor superlattice from these materials. He covered the surface of GaAs with $\text{Ga}_{1-x}\text{Al}_x\text{As}$ to form the n,p-junction. This configuration has a two-fold advantage in that the cell is 15% more effective than previous solar cell devices, and it has a rather large band gap. This band gap permits the whole spectrum to pass through it, and at the same time it can be doped to provide conductivity.

A semiconductor superlattice is composed of two semiconductors. The energy levels which result from the interaction of two potential wells, in addition to impurities, increase both electron promotion and residency. Greatly enhanced semiconductor characteristics emerge from the doped compositional superlattice. The challenge is to construct an n,p-junction semiconductor superlattice tailored to a specific need.

Construction of a Semiconductor Superlattice

The construction of an amorphous, hydrogenated silicon and germanium semiconductor superlattice, which has device applications, is chosen as an example. This type of superlattice can be built to a height of several hundred layers by means of plasma-assisted chemical vapor deposition (CVD), and can be examined by means of transmission electron microscopy (TEM).

An amorphous hydrogenated superlattice can be grown to many layers for several reasons.¹⁵ There are general superlattice requirements which can be relaxed or neglected by hydrogenating silicon and germanium semiamorphous crystals. First, the non-periodic crystal structure of the semiamorphous crystal minimizes the need for lattice matching previously described for the compositional superlattice. Second, hydrogen has the ability to passivate coordination defects. Third, TEM analysis allows the investigator to address construction problems before completing the superlattice.

Construction of a superlattice requires that the layers be smooth, the interfaces abrupt, and that the semiconductors be aligned at a 90° angle to one another. Alternating germanium and silicon layers are deposited on polished crystalline silicon wafers by means of an rf-plasma assisted CVD process. (CVD is the process where a material is heated until it condenses on the substrate). Alignment of the germanium and silicon layers is important, and a post is etched through the surface in order to examine the material by means of TEM.

A monodispersed layer of polymer is etched on the substrate pictured in Fig. 5 by means of an ion beam. The trough areas are preferentially removed leaving corridors. The conical structures are shaped from the remaining materials by means of dispersing a polymer with one locally thickened area. The thickened area is milled to a conical shape, removing about 50% in height of the semiconductor superlattice. The conical shape provides the proper structure to analyze by means of TEM. In fact, by controlling the polymer shape and orientation as well as the duration of the etch, thin sections 50-5000 Å thick and 3-55 mm long can be produced.¹⁵ Common construction defects include rippling and bifurcation structures. It is interesting to note that a rippled pattern does not promote instability in the crystal; the pattern is replicated but the interfaces do not become unstable as the film grows.

The defect which can produce spurious results is the bifurcation structure, which appears as a splitting either within a layer or at the junction between layers. It is thought that bifurcation occurs for one of the following reasons: (1) island growth from surface diffusion of depositing species (generally the result of growth by molecular beam epitaxy, a technique which will be described below); (2) an improperly controlled balance between deposition and etching during the film growth; or (3) local columnar growth.¹⁷

The TEM technique of analyzing superlattice cross-sections has shown that a superlattice can be grown and duplicated with relatively flat layers and abrupt interfaces at a 90° angle by means of plasma-assisted CVD, and that bifurcation structures are two-dimensional projections of the actual defect structure.¹⁸ New techniques using TEM are being developed to enhance image contrast in order to quantitatively analyze and grow superlattices on textured surfaces.

Molecular beam epitaxy (MBE) is another vapor deposition technique. The drawback to CVD is that predictions about electronic properties cannot be made because of the sample's non-uniformity and overall thickness. Similarly, when a crystal is made by means of MBE the sample may have the island growth due to surface diffusion. However, MBE has several advantages. First, low growth rate does promote less diffusion between layers even though island growth may occur. Second, growth is better controlled because it is conducted in an ultra-high vacuum (UHV) chamber. Third, because samples are made with periodic variations in composition, theoretical predictions were verified and other properties such as the quantum Hall effect were recognized.¹⁹

A molecular beam epitaxy apparatus consists of an ultra-high vacuum system, a substrate holder, furnaces, and instrumentation to control growth, and to clean and analyze the sample. Pressures in the range of 10^{-10} to 10^{-11} torr are routinely used. The sample is held in place with liquid indium as a glue to reduce dislocations during sample preparation and to transfer heat between the the block and the substrate. Stable temperature ranges in the furnace make it possible to produce uniform samples. The sample is cleaned in a UHV chamber. Auger, low-energy electron diffraction and reflection electron diffraction are used to characterize the surface of substrate prior to growth, as well as analyze structure during growth.²⁰

Construction of a semiconductor requires a clean environment, technique and care to faithfully reproduce crystals with specific characteristics for devices and energy cells.

Conclusion

Chemistry, physics and engineering have common themes, and the concepts used in science and engineering relate in a fundamental way.

The semiconductor superlattice can be understood by general concepts such as electron promotion, the Pauli Exclusion Principle, the nature of the chemical bond itself, crystallography, general parameters such as thermal agitation, chemical impurity and lattice defect, as well as physics to describe the potential well. The semiconductor superlattice can be made as a result of vapor deposition in conjunction with TEM analysis. In short, a reasonable basis set of a semiconductor superlattice includes chemistry, physics, and engineering/materials science.

The reason for such a diverse interaction of disciplines is the need to carefully characterize the chemical interaction between layers of varying interatomic distances and added impurity, as well as the need to determine the energy levels for the promoted electrons and the construction problems connected with layer alignment and surface texture.

Note: The omission of topical areas, as well as the mention of specific scientific teams and not others, is not meant to reflect on the quality of the contribution, but rather on the scope of this paper.

Acknowledgment: I am indebted to Abraham Abeles of Exxon (New Jersey) for sending me a number of articles to complement the seminar on semiconductors that he presented at the Spring 1985 MRS Meeting, San Francisco, and to my advisor, Leo Brewer.

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Table I Chemical Data of Selected Elements

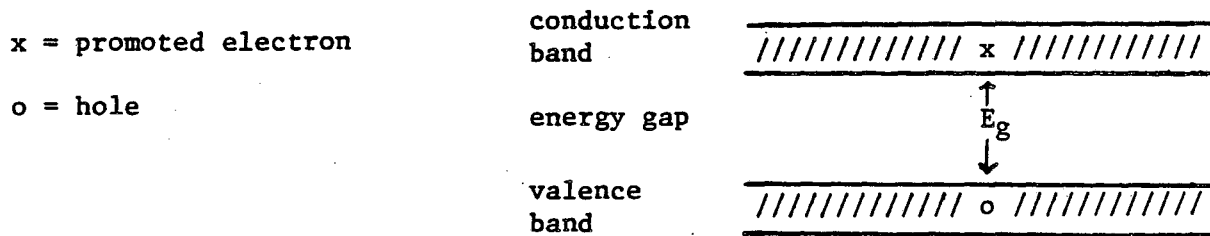
Element	Valence Electrons*	Lattice Type	Ionization Energy (eV,298K)	Classification
Silicon	$3s^23p^2$	cubic,diamond	8.151	semiconductor
Germanium	$4s^24p^2$	cubic,diamond	7.899	semiconductor
Selenium	$4s^24p^4$	hexagonal,mono	9.752	non-metal
Copper	$3d^{10}4s^1$	cubic,face-centered	7.726	metal
Oxygen	$2s^22p^4$	cubic	13.618	non-metal
Lead	$6s^26p^2$	cubic,face-centered	7.416	metal
Tellurium	$5s^25p^4$	hexagonal	9.009	semiconductor
Sulfur	$3s^23p^4$	orthorhombic	10.360	non-metal
Carbon	$2s^22p^2$	hex(graph),cubic(dia)	11.260	non-metal
Gallium	$4s^24p^1$	orthorhombic	5.999	metal
Arsenic	$4s^24p^3$	rhombohedral	9.88	semiconductor

* ground state of gaseous atom

Table II Semiconductor characteristics of the carbon family

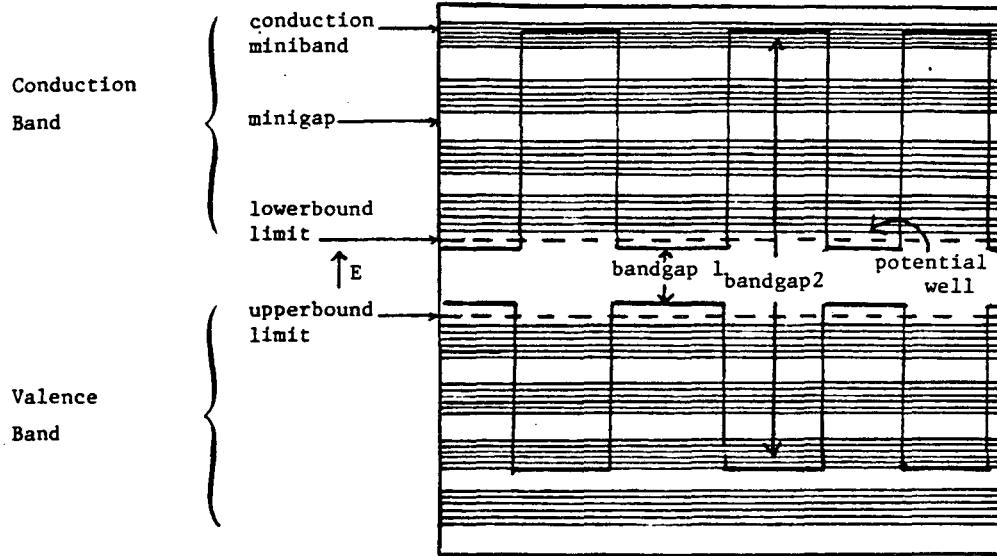
Element	Bond Energy (eV, 298K)	Interatomic Distance (Å)	Energy Gap (eV, 0K)
Carbon(dia)	3.7	1.54	5.4
Silicon	2.3	2.34	1.17
Germanium	1.93	2.44	0.744

Figure 2 Semiconductor electron recombination*



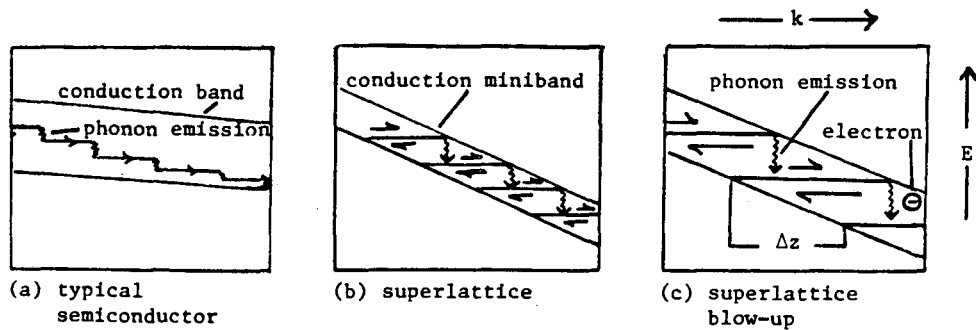
*Electron recombination describes the process whereby an electron is promoted from the valence to the conduction band, and then returns to the hole it left. Electron promotion, on the other hand, is merely the promotion of the electron from the valence to the conduction band.

Figure 3 Compositional semiconductor superlattice*



* Represents the interaction of two semiconductors and their resultant potential wells and modified bandgaps.

Figure 4 Bloch oscillation*

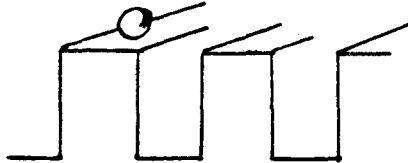


E = energy
k = wavevector

* Describes the difference between electron in the semiconductor vs. semiconductor superlattice.

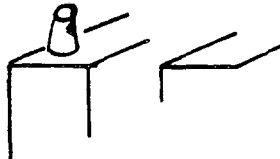
Figure 5 Construction of a conical post from a semiconductor superlattice*

Monodispersed polymer sphere is deposited on silicon substrate by means of reactive ion etching with a CCl_4 ion beam accelerated to 500 eV.



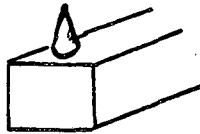
colloidal mask on scribed film

Polymer mask eroded, leaving post behind.



etched post structure

Mask completely eroded leaving a conical post with side wall angles of 60° , indicative of well-known ion milling faceting effects.



overetched conical post structure

*The post is constructed by etching away the semiconductor superlattice itself. The conical structure pictured in the third frame represents about half the height of the superlattice. The conical form can now be examined by means of TEM.

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