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Wide-bandgap semiconductor

Wide-bandgap semiconductors (also known as **WBG** semiconductors or **WBGSs**) are semiconductor materials which have a relatively large band gap compared to conventional semiconductors. Conventional semiconductors like silicon have a bandgap in the range of 1 - 1.5 electronvolt (eV), whereas wide-bandgap materials have bandgaps in the range of 2 - 4 eV.[1][2] Generally, wide-bandgap semiconductors have electronic properties which fall in between those of conventional semiconductors and insulators.

Wide-bandgap semiconductors permit devices to operate at much higher voltages, frequencies and temperatures than conventional semiconductor materials like silicon and gallium arsenide. They are the key component used to make green and blue LEDs and lasers, and are also used in certain radio frequency applications, notably military radars. Their intrinsic qualities make them suitable for a wide range of other applications, and they are one of the leading contenders for next-generation devices for general semiconductor use.

The wider bandgap is particularly important for allowing devices that use them to operate at much higher temperatures, on the order of 300 °C. This makes them highly attractive for military applications, where they have seen a fair amount of use. The high temperature tolerance also means that these devices can be operated at much higher power levels under normal conditions. Additionally, most wide bandgap materials also have a much higher critical electrical field density, on the order of ten times that of conventional semiconductors. Combined, these properties allow them to operate at much higher voltages and currents, which makes them highly valuable in military, radio and energy conversion settings. The US Department of Energy believes they will be a foundational technology in new electrical grid and alternative energy devices, as well as the robust and efficient power components used in high energy vehicles from electric trains to plug-in electric vehicles.[3] Most wide-bandgap materials also have high free-electron velocities, which allows them to work at higher switching speeds, which adds to their value in radio applications. A single WBG device can be used to make a complete radio system, eliminating the need for separate signal and radio frequency components, while operating at higher frequencies and power levels.

Research and development of wide-bandgap materials lags behind that of conventional semiconductors, which have received massive investment since the 1970s. However, their clear inherent advantages in many applications, combined with some unique properties not found in conventional semiconductors, has led to increasing interest in their use in everyday electronic devices to replace silicon. Their ability of handle higher energy densities is particularly attractive for attempts to continue obeying Moore's law, as conventional technologies appear to be reaching a density plateau.[4]

Contents

Use in devices

Wide-bandgap materials have several characteristics that make them useful compared to narrower bandgap materials. The higher energy gap gives devices the ability to operate at higher temperatures,[5] as bandgaps typically shrink with increasing temperature, which can be problematic when using conventional semiconductors. For some applications, wide-bandgap materials allow devices to switch larger voltages. The wide bandgap also brings the electronic transition energy into the range of the energy of visible light, and hence light-emitting devices such as light-emitting diodes (LEDs) and semiconductor lasers can be made that emit in the visible spectrum, or even produce ultraviolet radiation.

Solid-state lighting using wide-bandgap semiconductors has the potential to reduce the amount of energy required to provide lighting compared with incandescent lights, which have a luminous efficacy of less than 20 lumens per watt. The efficacy of LEDs is on the order of 160 lumens per watt.

Wide-bandgap semiconductors can also be used in RF signal processing. Silicon-based power transistors are reaching limits of operating frequency, breakdown voltage, and power density. Wide bandgap materials can be used in high-temperature and power switching applications.

Materials

There are many III–V and II–VI compound semiconductors with high bandgaps. The only high bandgap materials in group IV are diamond and silicon carbide (SiC).

Aluminum nitride (AlN) can be used to fabricate ultraviolet LEDs with wavelengths down to 200–250 nm.

Gallium nitride (GaN) is used to make blue LEDs and lasers.

Boron nitride (BN) is used in cubic boron nitride.

Materials properties

Wide bandgap materials are semiconductors with bandgaps greater than 3 eV.[2]

Bandgap

Quantum mechanics gives rise to a series of distinct electron energy levels, or *bands*, that vary from material to material. Each band can hold a certain number of electrons; if the atom has more electrons then they are forced into higher energy bands. In the presence of external energy some of the electrons will gain energy and move back up the energy bands, before releasing this and falling back down the bands again. With the constant application of external energy, like the thermal energy present at room temperature, an equilibrium is reached where the population of electrons moving up and down the bands is equal.

Depending on the distribution of the energy bands, and the "band gap" between them, the materials will have very different electrical properties. For instance, at room temperature most metals have a series of partially filled bands that allow electrons to be added or removed with little applied energy. When tightly packed together, electrons can easily move from atom to atom, making them excellent conductors. In comparison, most plastic materials have widely spaced energy levels that requires considerable energy to move electrons between their atoms, making them natural insulators. Semiconductors are those materials that have both types of bands, and at normal operational temperatures, some electrons are in both bands.

In semiconductors, adding a small amount of energy pushes more electrons into the *conduction band*, making them more conductive and allowing current to flow like a conductor. Reversing the polarity of this applied energy pushes the electrons into the more widely separated bands, making them insulators and stopping the flow. Since the amount of energy needed to push the electrons between these two levels is very small, semiconductors allow switching with very little energy input. However, this switching process depends on the electrons being naturally distributed between the two states, so small inputs cause the population statistics to change rapidly. As the external temperature changes, due to the Maxwell–Boltzmann distribution more and more electrons will normally find themselves in one state or the other, causing the switching action to occur on its own, or stop entirely.

The size of the atoms and the number of protons in the atom are the primary predictors of the strength and layout of the bandgaps. Materials with small atoms and strong, electronegative atomic bonds are associated with wide bandgaps. Elements high on the periodic table are more likely to be wide bandgap materials. With regard to III-V compounds, nitrides are associated with the largest bandgaps, and, in the II-VI family, oxides are generally considered to be insulators. Bandgaps can often be engineered by alloying, and Vegard's Law states that there is a linear relation between lattice constant and composition of a solid solution at constant temperature. The position of the conduction band minima versus maxima in the band structure determine whether a bandgap is direct or indirect. Most wide bandgap materials are associated with a direct bandgap, with SiC and GaP as exceptions.

Optical properties

The bandgap determines the wavelength at which LEDs can emit light and the wavelength at which photovoltaics operate most efficiently. Wide-bandgap devices therefore are useful at shorter wavelengths than other semiconductor devices. The bandgap for GaAs of 1.4 eV, for example, corresponds to a wavelength of approximately 890 nm, which is invisible infrared light (the equivalent wavelength for light energy can be determined by dividing the constant 1240 nm-eV by the energy in eV, so 1240 nm-eV/1.4 eV=886 nm). Therefore, GaAs photovoltaics are not ideal for converting shorter-wavelength visible light into electricity. Silicon at 1.1 eV (1100 nm) is even worse. For solar-energy conversion using a single junction photovoltaic cell, the ideal bandgap has been variously estimated from around 1.0 eV up to around 1.5 eV[6] (depending on various assumptions) because that low wavelength threshold covers nearly the entire solar spectrum that reaches the Earth's surface, but a lower-bandgap single-junction cell wastes a large portion of that power by inefficiently converting the shorter-wavelength parts of the solar spectrum. Because of this, a major area in solar energy research is developing multi-junction solar cells that collect separate parts of the spectrum with more efficiency, and wide bandgap photovoltaics are a key component for collecting the part of the spectrum beyond the infrared.

The use of LEDs in lighting applications depended particularly on the development of wide-bandgap nitride semiconductors.

The connection between the wavelength and the bandgap is that the energy of the bandgap is the minimum energy that is needed to excite an electron into the conduction band. In order for an unassisted photon to cause this excitation, it must have at least that much energy. In the opposite process, when excited electron-hole pairs undergo recombination, photons are generated with energies that correspond to the magnitude of the bandgap.

A phonon is required in the process of absorption or emission in the case of an indirect bandgap semiconductor, so indirect bandgap semiconductors are usually very inefficient emitters, although they work reasonably well as absorbers also (as with silicon photovoltaics).

Breakdown field

Impact ionization is often attributed to be the cause of breakdown. At the point of breakdown, electrons in a semiconductor are associated with sufficient kinetic energy to produce carriers when they collide with lattice atoms.

Wide bandgap semiconductors are associated with a high breakdown voltage. This is due to a larger electric field required to generate carriers through impact mechanism.

At high electric fields, drift velocity saturates due to scattering from optical phonons. A higher optical phonon energy results in fewer optical phonons at a particular temperature, and there are therefore fewer scattering centers, and electrons in wide bandgap semiconductors can achieve high peak velocities.

The drift velocity reaches a peak at an intermediate electric field and undergoes a small drop at higher fields. Intervalley scattering is an additional scattering mechanism at large electric fields, and it is due to a shift of carriers from the lowest valley of the conduction band to the upper valleys, where the lower band curvature raises the effective mass of the electrons and lowers electron mobility. The drop in drift velocity at high electric fields due to intervalley scattering is small in comparison to high saturation velocity that results from low optical phonon scattering. There is therefore an overall higher saturation velocity.

Saturation velocity

High effective masses of charge carriers are a result of low band curvatures, which correspond to low mobility. Fast response times of devices with wide bandgap semiconductors is due to the high carrier drift velocity at large electric fields, or saturation velocity.

Bandgap discontinuity

When wide bandgap semiconductors are used in heterojunctions, band discontinuities formed at equilibrium can be a design feature, although the discontinuity can result in complications when creating ohmic contacts.

Polarization

Wurtzite and zincblende structures characterize most wide bandgap semiconductors. Wurtzite phases allow spontaneous polarization in the (0001) direction. A result of the spontaneous polarization and piezoelectricity is that the polar surfaces of the materials are associated with higher sheet carrier density than the bulk. The polar face produces a strong electric field, which creates high interface charge densities.

Thermal properties

Silicon and other common materials have a bandgap on the order of 1 to 1.5 electronvolt (eV), which implies that such semiconductor devices can be controlled by relatively low voltages. However, it also implies that they are more readily activated by thermal energy, which interferes with their proper operation. This limits silicon based devices to operational temperatures below about 100 °C, beyond which the uncontrolled thermal activation of the devices makes it difficult for them to operate correctly. Wide-bandgap materials typically have bandgaps on the order of 2 to 4 eV, allowing them to operate at much higher temperatures on the order of 300 °C. This makes them highly attractive in military applications, where they have seen a fair amount of use.

Melting temperatures, thermal expansion coefficients, and thermal conductivity can be considered to be secondary properties that are essential in processing, and these properties are related to the bonding in wide bandgap materials. Strong bonds result in higher melting temperatures and lower thermal expansion coefficients. A high Debye temperature results in a high thermal conductivity. With such thermal properties, heat is easily removed.

Applications

High power applications

The high breakdown voltage of wide bandgap semiconductors is a useful property in high-power applications that require large electric fields.

Devices for high power and high temperature[5] applications have been developed. Both gallium nitride and silicon carbide are robust materials well suited for such applications. Due to its robustness and ease of manufacture, semiconductors using silicon carbide are expected to be used widely, create simpler and higher efficiency charging for hybrid and all-electric vehicles, reduced energy loss and longer life solar and wind energy power converters, and elimination of bulky grid substation transformers.[7] Cubic boron nitride is used as well. Most of these are for specialist applications in space programmes and military systems. They have not begun to displace silicon from its leading place in the general power semiconductor market.

Light-emitting diodes

In the near future, white LEDs with the features of more brightness and longer life may replace incandescent bulbs in many situations. The next generation of DVD players (The Blu-ray and HD DVD formats) uses GaN based violet lasers.

Transducers

Large piezoelectric effects allow wide bandgap materials to be used as transducers.

High-electron-mobility transistor

Very high speed GaN uses the phenomenon of high interface-charge densities.

Due to its cost, aluminum nitride is so far used mostly in military applications.

Important wide bandgap semiconductors

- Silicon carbide
- Silicon dioxide
- Aluminium nitride
- Gallium nitride
- Boron nitride, h-BN and c-BN can form UV-LEDs.
- Diamond

See also

- Band gap
- Direct bandgap
- Semiconductor
- Semiconductor devices
- Semiconductor materials

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