Low-Dimensional Materials: Unusual Properties and Applications in Nano-Electronics Devices

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In basic science, the terminology 'dimension' of an object is generally used to specify minimum number of coordinates require to identify a point within that object. For example, a point is a zero-dimensional (0D) object, a line is a one-dimensional (1D) object that has only length, a planar surface is a two-dimensional object (2D) with length and breath; a cube is a three-dimensional (3D) object which has length, breath as well as height. This simple parameter 'dimension' plays a very crucial role to determine the efficiency of several household devices, which we use often in our daily life.

Carbon (C) material graphite (3D) is a well-known material in the industry since sixteenth century as it is the only non-metal element which is a good conductor of electricity. Leads of pencils are the most common use of graphite in everyday life. Besides, natural graphites are also used in batteries, lubricants, steel making, and brake lining.

A breakthrough in this graphite industry occurred in the year 2004, when a group of scientists (KSNovoselov, AKGeim et al.) from the University of Manchester were able to isolate a single layer of graphite for the first time. This 2D single layer of graphite is popularly known as graphene sheets in material science family.

Invention of graphene opens a new door to the scientists in the field of both basic as well as applied science background. Properties of 2D grapheme is different from its bulk conformation graphite in many aspects, which make this 2D material very special. Thickness of a single layered graphene is of the order of very few nanometre (1 nanometre = 10^{-9}metre) or less than that. As a

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result, electrons are confined mainly tothe surface of the material rather than its volume. So, surface properties are predominant in this kind of ultrathin 2D material, which are generally abbreviated as nano-materials. Devices designed with graphene are not only extremely compact, but they are also very cheap the from financial point of view as carbon is a highly abundant material in nature. During last few years, a large number of theorists and experimentalists have devoted their research concerns to explore different properties of graphene so that the material can be used effectively to fabricate various devices needed in the industry as well as day-to-day life.

Inspired by the advancement of low-dimensional materials family in last few years, we have concentrated to analyse several properties of this kind of (graphene) material theoretically so that it may help the experimentalists to design novel devices.

Band gap is a basic parameter to specify the significance of any material for device fabrication. It is well-known that every material consists of several energy bands and electrons stay in these energy bands. The bands which are filled by electrons are conventionally known as valence bands (VB) and the energy bands where no electrons exist are called conduction bands (CB). Electrons in VB are tightly bound to the atoms and they are unable to move freely so, they are called bound electrons. However, an electron can move from VB to CB if some excitations are given to that electron. Illumination of light energy, giving some external electric or magnetic fields can be regarded as excitation for an electron. Thus, an electron has to overcome a finite amount of energy to move from VB to CB and this energy value is generally called as band gap of that material. Electrons in CB are free to move and so they are called free electrons.

After analyzing band gap of graphene, scientists have confirmed that, graphene is not metal, or semiconductor or insulator. Rather it is something special, called semi-metal, where band gap is zero, but this band gap can be opened.

Along with the band gap, optical properties like absorption coefficient, refractive index, reflectivity, electron energy loss spectra (EELS) are some basic but important parameters in the field of material physics. All these parameters are formally called as opto-electronic properties of a material and they play a vital role in designing ultrafast opto-electronic devices.

We have focused our research interest to investigating about graphene quantum dots schematically. If the two dimensions of graphene can be restricted (or confined), then the configuration is a 0D object. This kind of confined graphene sheets are known as graphene quantum dots or simply GQDs. GQDs exhibit many interesting and unconventional properties, which make this material so important. Our results indicate that, GQDs can be used as a good reflector device in nano-industry. The results of this investigation are reported in the 'Journal of Physics and Chemistry of Solids 99 (2016) 34–42'.

Even after successful investigations and applications of graphene, researchers continue their intensive research work to search for more graphene-like 2D material. As a result, a new material named germanene has got its entrance in this 2D material family very recently. A group of scientists ME Davila et al. introduced this material in 2014 for the first time experimentally. This material is just like graphene, but the C atoms of graphene are replaced by germanium (Ge). That is why germanene is called germanium, a counter part of graphene. In recent times, germanene demands potential application in nano-electronics.

We have analysedopto-electronic and magnetic properties of germanene recently. Germanene is semi-metallic in nature just like graphene. Our study revealed that finite band gap is opened by decorating germanene with foreign elements. Finite band gap opening is necessary for semiconductor device application of a material. We found that a band gap of the order of 287 me Vopens (A: See change) in germanene, which is quite suitable for transistor device applications. The results of these studies have been reported in the international journals 'Current Applied Physics 17 (2017) 573–583', 'Current Applied Physics 17 (2017) 1589–1600' and 'Journal of Physics and Chemistry of Solids 115 (2018) 332–341' schematically.

In conclusion, our investigations reveal that 2D materials like graphene, germanene are very important from scientific point of view. These materials can be used efficiently to design electronic devices like smart phones, laptops, microwaves, laser and photo-detectors, photo-voltaics devices, and optical modulators, which are essential in daily life as well as the industry. We have explored several unusual properties of these materials by numerical methods which may be helpful to design novel, smart, efficient as well as low-cost digital gadgets. Opto-electronic properties of these materials are so surprising and unconventional that, they still demand serious research concerns for smart development of our society. We hope, our work may act as a motivation to the readers to study further with low dimensional materials and may shed light to develop graphene and beyond graphene (germanene) elements based nano-industry.