

Methods for Improving the Mobility of Semiconductor Carriers

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Abstract. Semiconductor is the core of the information technology industry and a leading industry supporting economic and social development. Its products are mainly used in various fields such as computers, digital electronics, electrical, transportation, medical, aerospace, and so on. In recent years, the semiconductor application field has been continuously expanding with technological progress, and emerging fields such as 5G, artificial intelligence, intelligent driving, robotics, and drones have flourished, bringing new opportunities to the semiconductor industry. The main properties of semiconductors include conductivity, internal field, carrier concentration, and mobility. These properties are influenced by factors such as the preparation, processing technology, and device design of semiconductor materials. Among them, mobility is an important physical quantity that marks the speed of semiconductor carrier movement under the action of an electric field, and its size directly affects the working frequency and speed of semiconductor devices and circuits. For bipolar transistors, high carrier mobility can shorten the time for carriers to cross the base region, increase the characteristic frequency, and effectively improve the frequency, speed, and noise performance of the device. For field-effect transistors, improving carrier mobility is of greater significance. Therefore, this article summarizes different methods for improving semiconductor carrier mobility, including reducing impurities and defects, controlling lattice structure, adjusting doping element concentration, and intermolecular stacking. This page also describes the areas in which semiconductors with high carrier mobility are used, to serve as a reference for future semiconductor research.

Keywords: Semiconductor, carrier mobility, improvement methods.

1. Introduction

1.1. Semiconductor

At room temperature, a semiconductor is a substance that conducts electricity between a conductor and an insulator. Its development began around 200 years ago, according to its history. The famous British physicist and chemist Michael Faraday first identified the phenomenon of semiconductors in 1833. In an experiment, he found that contrary to the resistance properties of common metals, the resistance of silver sulfide increased with temperature rather than decreased. Following public interest in this strange occurrence, the French scientist Becquerel discovered the semiconductor photovoltaic effect in 1839. Immediately after more than thirty years, the British Smith selenium crystal material under the light found that its electrical conductivity increased, which is the third effect of semiconductors - the photoelectric conductivity effect. A year following this finding, in 1874, German physicist Braun made the first observation that the conductivity of certain sulfides has a direction. Since that time, the rectification effect, the fourth characteristic of semiconductors, has also been identified. The point-contact transistor was developed by Bardeen and Brattain at Bell Labs in late 1947, and Shockley's junction transistor appeared a few months later. Even though these features had long been known, it wasn't until these developments that the age of semiconductors was fully ushered in.

1.2. Development History

Since the invention of the semiconductor in 1947, countless scientists have devoted themselves to exploring the path of semiconductor development. In 1948 and the following five years, despite the efforts of several companies, only electro-crystals with germanium as the contact point were produced.

It was not until May 1954 that the first silicon transistor was successfully developed. Although the advent of the transistor made up for the shortcomings of the electron tube, making and using electronic circuits required the manual assembly of various components, which was impractical. Thus, the integrated circuit was born. Soon after, Fairchild produced the world's first working monolithic integrated circuit, and since then, integrated circuit technology has been formally commercialized. In the same year, Bell Labs developed epitaxial technology, so that the semiconductor can batch production, which also marks the semiconductor industry has entered the era of high-speed development. 1961, in the U.S. Air Force under the commission the first integrated circuit-based computer was successfully invented by Texas Instruments, and at the same time, NASA (National Aeronautics and at the same time, NASA (National Aeronautics and Space Administration) also showed great interest in this technology and used it in the aerospace field. The following year, integrated circuits were used in missiles, the first time semiconductor technology was used in the military. Moore, one of Intel's co-founders, developed the renowned Moore's Law, which asserts that the number of transistors that can be accommodated on an integrated circuit doubles every year and a half to two years, as integrated circuits are being employed in an increasing number of applications. In 1969, the first ever microprocessor was developed by Intel, named the 4004, followed the next year by the world's first digital watch, the Pulsar, priced at \$2,100 by Hamilton. Throughout the 1970s, the IC industry was still only production-orientated, but in 1982, the digital signal processor was born, a new product invented by Texas Instruments that ushered the world into the digital age of infinite possibilities. The broad prospects for development drove the rise of standard process lines, and in 1987, TSMC was founded as the world's first standard process plant. The following year, 16M DRAM was introduced, and its appearance meant that the semiconductor industry has since entered the ultra-large-scale integrated circuit stage to this day.

1.3. Problems faced

As semiconductor technology continues to advance, so does our need for it. However, demand has not kept pace with technology growth, which has led to several problems. The first is the challenge of process technology. Current chip sizes are getting smaller and smaller, but as the size shrinks, the process requirements also increase, and it is difficult for existing technologies to support Moore's Law. How to optimize the innovative process technology is the first challenge we face, we are looking for ways to improve the performance of silicon-based semiconductors at the same time, while also trying to find other possible semiconductor materials. Secondly, the power consumption of semiconductors is an issue. Nowadays, the performance requirements of devices are increasing rapidly, and we must ensure the performance while improving the efficiency of the chip to make more efficient use of energy, which requires us to improve the carrier mobility of semiconductors. Furthermore, as semiconductors are increasingly penetrating people's lives, the information security of semiconductor devices also needs to be guaranteed urgently. In addition to these three, various challenges await us, such as improving RF performance, controlling the effects of quantum effects, and developing efficient and high-quality semiconductor storage devices. Currently, the most urgent need is to improve the carrier mobility of semiconductors.

2. Methods for improving semiconductor carrier mobility

2.1. Reduction of impurities and defects

The doping of semiconductors with impurities affects their electron mobility, and the Brooks-Herring (BH) theory, which states that the electron-impurity scattering potential is based on a constant impurity charge, clearly ignores the specific information on the density distribution and shielding of the impurity charge in solids. Although some new theories have emerged on top of this, they are too crude to give precise results. The results of a current experiment show that in silicon-based semiconductors, the scattering of electron carriers by ionized donor impurities is significantly stronger than that by recipient impurities, and that n-type doping affects the electron mobility of

semiconductors differently from p-type doping [1]. According to experimental data, when the carrier concentration is higher than 10^{19}cm^{-3} , phosphorus doping is more effective in improving carrier mobility than arsenic doping. Meanwhile, there are additional experiments that show that some innate defects can greatly reduce the carrier mobility, so they try to use, for example, photoproduction to introduce excess carriers to change the enthalpy of semiconductor defects, and thus suppress the defect population during crystal growth or annealing [2]. It is also important to note that doping silicon nanocrystals with nanoscale phosphorus may effectively boost the carrier mobility, with an electron mobility of up to $30.3\text{cm}^2/\text{V s}$, which is significantly greater than that in the undoped case [3].

2.2. Control of lattice structure

Cadmium telluride (CdTe) is a material that can be used in the manufacture of photovoltaic cells, but the difficulty of producing low and stable ohmic contacts greatly limits its application. However, it has been shown that thermally treating CdTe with copper and injecting it may significantly alter its electrical characteristics. In this work, copper was introduced into the CdTe films by evaporating them onto a glass substrate at a consistent temperature, submerging them in copper nitrate for 30 minutes, and then annealing the films for another 30 minutes at various temperatures. The film underwent this treatment, and the band gap was decreased from 1.50eV to 1.37eV. The semiconductor was discovered to be a p-type semiconductor, and due to its good characteristics, it may be used in solar cells [4].

Colin et al. discovered that crystallinity and microcrystalline orientation may be precisely controlled. For the best performance of polymer electrical devices like field-effect transistors, morphological control from the molecular to the macroscopic scale is useful. Liquid crystal intermediate phases have been shown to develop in semiconducting polymers with branched side chains, although the stacking distance is enhanced by spatial repulsion from the side chain structure. This change to the crystal cell affects electron transport adversely. In cyclopentylenedithiophene-benzothiadiazole donor-acceptor copolymers, the branching point is progressively shifted farther from the conjugated backbone, resulting in a smaller stacking distance. These materials maintain their advantageous liquid crystal properties despite the shift in the unit lattice, which is accompanied by a monotonic increase in carrier mobility in the field effect transistor. The branching sites that are furthest from the polymer backbone have the greatest mobility values, which vary from roughly 10^{-4} to $0.41\text{ cm}^2\text{ V}^{-1}\text{ s}^{-1}$ [5].

2.3. Adjustment of doping concentration

Field effect tubes, which are typically created via a two-step growth procedure, show perfect metal/semiconductor interactions in van der Waals heterostructures comprising metallic (m-) and semiconducting (s-) transition metal disulfide compounds (TMDs). However, during chemical vapor deposition of them, m-TMDs are synthesized on pre-grown s-TMDs, which seriously affects the doping of s-TMDs. Thus, some experiments pointed out that Nb-doped WSe_2 and van der Waals heterostructures of metal/doped semiconductors with controllable doping concentration could be synthesized by a one-step growth method [6]. The mobility and switching ratio may be increased by an astounding 1238 and 4400 times, respectively, by changing the doping concentration, and the RC value utilizing NbSe_2 contacts is only 2.46k.m, which is substantially lower than that using metal contacts. The future synthesis of diverse metal-doped semiconductors will be guided by this technique [6]. Konstantin et al. observed that the number of M ions engaged in the scattering process depends on the effective mass of charge carriers and used the M ion scattering model to explain the differences in electron mobility of n-Si bulk crystals strongly doped with phosphorus and arsenic [7].

As an important component of organic field-effect transistors, organic semiconductor materials have a significant impact on device performance. Compared with small molecule semiconductor materials, polymer semiconductor materials have received extensive attention and research due to their advantages of easier solution processing and room temperature preparation. From the 1970s to

the present, polymer semiconductor materials and their optoelectronic devices have been developed by leaps and bounds. Through the researchers' continuous exploration and innovation, various kinds of polymer semiconductor materials with novel structures have emerged one after another, and the device preparation process has been optimized and improved, which has improved the carrier mobility of polymer field-effect transistors from $10^{-5} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ in the early stage to $36.3 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ nowadays, and accumulated rich experience in the design and synthesis of the molecular structure of the polymer field effect materials, and also its intrinsic structure. We have accumulated rich experience in the design and synthesis of polymer field-effect material molecular structures, and the intrinsic charge transport mechanism has also been clarified with the improvement of material and device properties.

2.4. Intermolecular stacking

In recent years, organic semiconductors have been developing rapidly, and their enormous potential is very promising. However, carrier migration is still a challenge for organic semiconductors at present. The usage of the herringbone structure with "-" stacking has been proved experimentally, and this mode is more efficient for screening high-mobility materials. Materials having acene-like frontier orbital nodes and eclipsed packing have been discovered to be capable of achieving high brightness and mobility [8].

3. Applications of high-mobility semiconductors

3.1. Intermolecular stacking

An organic light-emitting diode (OLET) is a material that is capable of transmitting signals with optical properties while transmitting electrical signals. It can display desired circuits at a low cost, and its fabrication process is simple, components are easy to synthesize, and it has a wide range of applications. In addition to being employed as a charge transfer and luminous layer, PDI-C13 has also been thermally annealed and had the length of its channels cut to boost its current density and counteract luminescent bursts. The device's long-term stability and electron mobility are enhanced by this technique. However, more external quantum and coupling efficiency is needed to properly promote the usage of OLET in daily life. According to Toffanin et al., an organic photovoltaic device that is transparent, highly integrated, and multifunctional has an order of magnitude more brightness and optical power than polymer dielectrics. However, there are still a lot of difficulties in synthesizing high-mobility organic semiconductor devices [9].

3.2. Organic photodetectors

The goal of current research is to increase the mobility and stability of the organic photodetector (OPD), the fundamental component of image sensing and optical communication technology. In comparison to conventional semiconductor materials, it offers extremely clear benefits due to its simpler integration, molecularly programmable characteristics, and distinctive structure-property connections. In one of the better studies on OPDs, linear single-crystal dibromo-platinum (II) diimide complexes with layered architectures and fluorine-containing chain segments were used in the experimental production of active-layer semiconductor materials. This experiment demonstrated the stability of the device with superb optical switching and a wide range of possible applications. A semiconductor phototransistor with high carrier mobility and great responsiveness across a broad spectrum range was created by Guan et al. based on n-type tiny molecule semiconductors [10].

3.3. Gas sensors

Device materials for sensing ammonia gas can be made of organic semiconductors. Organic molecules have distinct electrical and mechanical characteristics and are simple to create since they are artificially free to alter substituents. It is feasible to sensitively detect changes in the concentration

of ammonia gas in the environment using these organic small molecule systems with particular functional groups because they are sensitive to environmental changes that modify the carrier transport capabilities. Although the device is negatively impacted by the ions of the n-type semiconductor's great propensity to stabilize radical anions, this challenge has been solved. The findings of the studies demonstrate that a novel approach for the creation of extremely sensitive ammonia sensor devices is offered by the molecular engineering of effective SRAFs.

4. Summarize

Semiconductors, which have uses in integrated circuits, consumer electronics, communication systems, solar power production, lighting, and high-power power conversion, are materials having conductivity that is intermediate between conductors and insulators at room temperature. The significance of semiconductors is immense from the viewpoint of technological or economic growth. Semiconductors serve as the central components of the majority of electronic goods, including computers, mobile phones, and digital recorders. Improving carrier mobility is an essential part of improving the performance of semiconductor devices. This article summarizes the existing methods for improving semiconductor carrier mobility and introduces the applications of high-carrier mobility semiconductors in different directions. However, it is very difficult to improve carrier mobility in both organic and inorganic semiconductors. In addition, in addition to the material itself, the external environment can also affect the mobility of semiconductor charge carriers. For example, as the temperature increases, the lattice vibration intensifies, thereby increasing the interaction between charge carriers and the lattice, and reducing the mobility of charge carriers. Therefore, it is imperative to develop new methods in future research.

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