The Applications of Low melting point metals in semiconductor materials

Chang Liu[1, *], Chongquan Wang[2]

[1]Department of Chemistry, Northeast Forestry University, Harbin China

[2]Zouping No. 1 Middle School Binzhou China

*Corresponding author: 2023214842@nefu.edu.cn

Abstract. This summary furnishes an elaborate analysis of the integration of LMP metals with semiconductor materials. To commence, the article delineates the selection criteria, which incorporate the physical and chemical traits of low-melting-point metals, their thermal stability and fluidity across diverse temperature intervals. These components are indispensable for guaranteeing the most favorable contact and adhesion between the metal and the semiconductor. Subsequently, a meticulous examination is carried out on the interactions between low-melting-point metals and semiconductors, covering not only physical couplings but also chemical reactions and alterations in interface properties. Moreover, this summary briefly expounds on how LMP metal-embedded semiconductor materials can be utilized in solar cells. This portion focuses on how such composite architectures can enhance photoelectric conversion efficiency while accentuating their manufacturing benefits. Finally, it emphasizes potential applications and future prospects for this composite material within the domains of microelectronics and energy storage.

Keywords: LMP metals; Semiconductor materials; Semiconductor applications.

1. Introduction

LMP metals are crucial for research in semiconductor materials and significantly contribute to improving photo electrochemical water splitting, as well as advancing solar cell technologies. The rapid expansion of the electronics industry has led to an increased demand for high-performance semiconductor materials, resulting in a greater need for varied applications. This trend has spurred ongoing research into novel electronic materials and production methods.

The distinctive physical and chemical attributes of LMP metals, such as exceptional electrical conductivity, malleability, and the capacity to retain liquids at room temperature, have positioned them at the cutting edge of semiconductor materials research. These characteristics endow LMT metals with considerable potential for use in semiconductor applications, particularly within flexible electronics and wearable devices. As electronic gadgets continue to shrink in size while requiring more flexibility and intelligence, conventional rigid materials and manufacturing techniques face challenges in meeting these heightened performance expectations.Issues related to stability, compatibility, processing during application must be effectively tackled. The introduction of low melting point metal providesa revolutionary material alternative for the electronics sector;its combination of plasticity and conductivity generates numerous innovative opportunities.

2. LMP Metals in semiconductor materials

2.1. LMP metals

The LMP metal is used to describe metals that exist in a liquid state at temperatures that are relatively low or near-zero. Examples of these metals include mercury,germanium, indium and bismuth. These metals possess low melting points and high surface tensions, which confer distinctive advantages in specific applications. Common materials exert a vital role in diverse scientific and industrial applications. At low temperatures, mercury (Hg), gallium (Ga) and indium (In) are used more, while commonly used semiconductors include silicon (Si), germanium (Ge), gallium arsenide (GaAs), indium phosphide (InP), gallium nitride (GaN), silicon carbide (SiC) and zinc oxide (ZnO).

The physical properties of low melting point metals are manifested in the following ways, These metals display excellent electrical conductivity, which can even exceed that of certain solid metals. Additionally, these metals exhibit high surface tension, which enables the formation of stable droplets under specific conditions. Moreover, they exhibit distinctive chemical properties, including augmented strengthening, proclivity for reactions,and superior oxidation resistance. These attributes facilitate the formation of distinctive interface layers when combined with semiconductor materials, where they play a crucial role.

2.2. Semiconductor materials

When applying liquid metals to semiconductor materials, we need to focus not only on the stability of the interface between liquid metals and semiconductors, material compatibility and appropriate temperature, but also consider cost effectiveness and environmental impact. Traditional semiconductor materials often rely on high-temperature processing and strict vacuum conditions, which requires us to develop new low-temperature manufacturing technologies. Therefore, it is necessary to search for materials with high electron mobility, suitable bandgap width, low temperature processing capacity,and economic energy saving.

2.3. Interaction between low-temperature liquid metal and semiconductor

When a metal with a low melting point comes into contact with a semiconductor, a special metal-semiconductor interface layer is formed. When a liquid metal comes into contact with a semiconductor, a metal-semiconductor (M/S) junction can be established. This junction typically manifests in two forms. The first is Schottky barrier and Ohmic contact[1]. Schottky Barrier. When a metal interfaces with an N-type (electron-dominated) semiconductor, an energy barrier known as the Schottky barrier is established if the work function of the metal is lower than the electron affinity of the semiconductor. In this case, electrons must overcome this barrier to be injected from the semiconductor into the metal. The height of the Schottky barrier depends on both the work function of the metal and the electron affinity of the semiconductor. In practical applications, Schottky barriers are employed in constructing Schottky diodes, which exploit the rectification properties inherent to metal-semiconductor junctions. The second is Ohmic Contact. Ideally, Ohmic contact refers to establishing a low-impedance connection between a metal and a semiconductor that permits charge carriers to traverse their interface freely without generating significant energy level barriers. In practice, through appropriate doping and metallization techniques, It is feasible to acquire properties analogous to ohmic contact, which is a fundamental requirement for fabricating electrodes in semiconductor devices.

In this interaction [2], the electronic structure of the interface can be regulated, and the electron energy level arrangement at the interface can be optimized by alloying or doping the liquid metal work function, so as to improve the charge transport efficiency. In addition, liquid metals can also be used as catalysts to promote the synthesis and growth of semiconductor materials.

Chen et al. [3] explored the ultra-high mobility layered oxide semiconductor Bi_2O_2Se, with their research focusing on this category of semiconductor materials. Existing literature reveals that Bi_2O_2Se, exhibits exceptionally high carrier mobility, featuring a Hall mobility of 280,000 $cm^2/V\cdot s$ at low temperatures and an apparent field-effect mobility around 2000 $cm^2/V\cdot s$ at room temperature. This characteristic positions Bi_2O_2Se, as having significant potential for applications in high-speed electronic devices. Furthermore, the band gap of Bi_2O_2Se, is roughly 0.8 eV, indicating its promising applicability in optoelectronics and electronics sectors. Concurrently, Its effective electron mass is extremely small,merely approximately 0.14 - 0.15m, which is beneficial for the rapid transfer of electrons. Consequently, this material is ideally adapted to fulfill the requirements related to the integration of low melting point metals into semiconductors.

3. Preparation Method

3.1. Metal Film Embedding Method

The preparation of low-temperature liquid metals typically involves the melting of high-purity metals,such as indium. This process requires placement in a high-heat-resistant container and heating at elevated intensities to prevent oxidation reactions induced by atmospheric oxygen. When the liquid metal serves as an electrode in contact with a semiconductor, effective charge injection and collection can be achieved,thereby enhancing device performance. Nevertheless, under standard circumstances, numerous surfaces pose challenges for the wetting of liquid metals, complicating the formation of a stable bond between the two materials.

To address these issues,researchers at the Institute of Metal Research within the Chinese Academy of Sciences conducted experiments aimed at optimizing the specialized film structure that exists between conductive fluids and semiconductor light-absorbing materials[4]. This optimization was accomplished by adjusting the composition of liquid metal to modify its work function. Specifically, zinc oxide particles were embedded in indium tin (In-Sn) for the creation of ohmic contacts, while Bi-In-Sn was incorporated for the formation of Schottky contacts. The resultant compositional optimization significantly enhances photoelectrochemical hydrolysis activity and plays a crucial role in improving the performance of semiconductor photoelectrodes.

3.2. liquid metal direct printing technology.

Research [1,5] institutions have made significant achievements in the field of manufacturing advanced semiconductor materials using liquid metal direct printing technology. Researchers have developed an innovative single-step low-temperature printing process, successfully achieving n-type and p-type doping of gallium oxide (Ca_2O_3) semiconductor materials. This technological breakthrough simplifies the traditional multi-step doping process, with the entire production process carried out at lower temperatures, greatly improving production efficiency and reducing costs. It provides an efficient and economical new method for large-scale production of gallium oxide semiconductor materials and their electronic devices. In addition,the institution has proposed a new concept of liquid metal combinatorial chemistry and its theoretical system,which comprehensively covers the various combination possibilities of liquid metals and material innovation paths. This lays a theoretical foundation for designing and developing new materials with diverse functions and properties according to specific needs in the future. In research on low melting point-induced technology, researchers have successfully prepared low-temperature polycrystalline silicon by using nickel metal as a catalyst to promote the transformation from amorphous silicon to polycrystalline silicon. This technology, known as metal-induced lateral crystallization technology, can produce high-performance polycrystalline silicon thin-film transistors (TFT) under lower temperature conditions, which is of great practical value for manufacturing high-performance display devices and achieving system integration. The advantages of this method are a wide selection of materials, ease of manufacturing complex structures,and an efficient and low-cost production method.

4. Applications in semiconductor

4.1. 2D electronic materials

Shengqi Wang et al. [6] have developed an innovative technique that employs liquid metal for intercalation, leading to the successful formulation of various inks derived from two-dimensional electronic materials. This pioneering approach enables a variety of two-dimensional crystal powders -encompassing transition metal dihalogenated compounds (TMDs), main group metal sulfides, terpolymer layered crystals, layered oxides and elemental crystals to be transformed into solution-processable two-dimensional semiconductors at room temperature.

By taking advantage of the conductive and adhesive properties of liquid metals [7], this method yields large-area thin films with outstanding conductivity and mechanical durability on diverse substrates. Notably, it also supports the intercalation and exfoliation of monolayer inks from wide-bandgap semiconductors. Through this technique, researchers can fabricate high-performance large-area electronic devices such as thin-film transistors and memory components, providing a flexible and efficient preparation strategy for employing 2D materials in electronics and optoelectronics.

4.2. Liquid Metal printing technique.

Andrew B. Hamlin, YouxiongYe et al. [8,9,10]have innovatively introduced a liquid metal printing methodology for the creation of two-dimensional InOx transistors that demonstrate an exceptionally high quality factor. This pioneering technique capitalizes on the inherent oxidation of liquid indium to expedite the oxidation process and generate consecutive nanosheet layers. Consequently, it attains remarkable printing velocities of up to 60 cm^2/s. The nanocrystalline LMP InOx film fabricated showcases a distinctive two-dimensional grain architecture that augments both electrical conductivity and other related properties. Through modulating the band structure and electron state density in the 2D InOx channels via quantum confinement followed by low-temperature oxidation annealing, they successfully achieved ultra-high mobility (V_0= 67 $cm^2\ V^{-1}s^{-1}$). This advancement significantly mitigates hysteresis effects, facilitating the transistor to operate with enhanced speed and stability during switching operations. Thus, this enhancement gives rise to an improved response speed and reliability in the overall circuit performance.

5. Conclusion

This research investigates the utilization of LMP metal-embedded semiconductor materials in solar photo catalytic water splitting for hydrogen generation, providing an extensive analysis of interface factors. Our study reveals that the preparation method for this material offers numerous advantages, including broad applicability, high structural integrity of the membrane, ease of scalability and simple recovery of raw materials. The interface factors between LMP metals and semiconductor materials include the relationship between work function matching in semiconductors and liquid metals. Selecting suitable liquid metals to contact with semiconductor particles and differences in work functions among various liquid metals (such as indium-tin alloy and bismuth-indium-tin alloy), which affect their interaction types with semiconductors and subsequently influence photo electrode performance. Importantly, we have identified key characteristics of In-Sn alloy, its low melting point makes it a fitting choice as an LMP metal, thus facilitating the creation of these composite semiconductor materials. Additionally, In-Sn alloy exhibits excellent thermal conductivity,improving thermal management capabilities in photocatalytic applications. Its superior electrical conductivity enhances electron transport efficiency, thereby boosting the photoelectric performance of the photoelectrode. LMP metal-embedded semiconductor materials possess a wide range of applications, particularly in solar photocatalytic water splitting for hydrogen generation, where In-Sn alloy-based composites can facilitate efficient and economical hydrogen production. Additionally,due to their intrinsic flexibility, IN-SN alloys can be incorporated into flexible matrices for the development of advanced flexible electronic devices.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

References

[1] Giuseppe Greco, Ferdinando Iucolano, Fabrizio Roccaforte et al. Ohmic contacts to Gallium Nitride materials. Applied Surface Science, 2016, 383: 324-345.

[2] XiangtaoChen, Chao Zhen, Jianhang Qiu et al. Modulating band alignment at the 3D metal/semiconductor interface of liquid metal-embraced semiconductor photoelectrodes for water splitting. Science China Meterial, 2024, 67(6): 1804-1811.

[3] Cheng Chen, Meixiao Wang, Jinxiong Wu et al. Electronic structures and unusually robust bandgap in an ultrahigh-mobility layered oxide semiconductor, Bi2O2Se. Science Advances, 2018, 9(4).

[4] Yiyu ZhangDasari VenkatakrishnaraoMichel Bosman et al. Liquid-Metal-Printed Ultrathin Oxides for Atomically Smooth 2D Material Heterostructures. ACS Nano, 2023, 17(8): 7929-7939.

[5] Qian Li, Bang-Deng Du, Jian-Ye Gao et al. Liquid metal gallium-based printing of Cu-doped p-type Ga2O3 semiconductor and Ga2O3 homojunction diodes. Applied Physics Reviews, 2023.

[6] Shengqi Wang, Wenjie Li, Junying Xue et al. A library of 2D electronic material inks synthesized by liquid-metal-assisted intercalation of crystal powders. Nature Communications, 2024, 15(1): 6388.

[7] Qian Li, Ju Lin, Tian-Ying Liu et al. Gas-mediated liquid metal printing toward large-scale 2D semiconductors and ultraviolet photodetector. npj 2D Materials and Applications, 2021, 5(1): 36.

[8] Yujia Song, Jingyi Li, Ju Wang et al. Liquid Metal-Printed Semiconductors. Advanced Engineering Materials, 2024.

[9] AndrewB.Hamlin, Youxiong Ye, Julia E. Huddy et al. 2D transistors rapidly printed from the crystalline oxide skin of molten indium. npj 2D Materials and Applications, 2022, 1(6): 16.

[10] Qian Li, Bang-Deng , et al. Room-Temperature Printing of Ultrathin Quasi-2D GaN Semiconductor via Liquid Metal Gallium Surface Confined Nitridation Reaction. Advanced Meterials Technologies, 2022, 7(11).