ISSN 2959-6157

Research of Silicon and Zinc Oxide

Yiran Yang

Ulink College of Shanghai, Shanghai, China
yiran.yang@ulink.cn

Abstract:

As electronics develops, zinc becomes more and more useful and electronics producers consume more and more silicon because of it is abundant, it has a mature processing technology and it has a high carrier mobility. Those advantages made silicon perfect for integrated circuits. However, in some cases, silicon is no longer the best choice. Despite silicon's advantages, there are problems for silicon. For example low breakdown voltage, low thermal conductivity and indirect band gap. Although silicon is still the most commonly used semiconductor, another type of semiconductor, zinc oxide starts to become more and more important in electronics. However, the two materials are used differently. This paper aims to provide the various properties of silicon and zinc oxide, and explain the reasons for their applications in electronics. The two materials are indispensable although they have a lot of disadvantages. Engineers must carefully consider the advantages and limitations of each material for specific applications to make optimal material selections.

Keywords: Semiconductors; silicon; zinc oxide.

1. Introduction

Since the 21st century, third generation semiconductors have developed rapidly. Notable examples such as zinc oxide, gallium nitride, and silicon carbide have become irreplaceable in the field of electrical engineering. Zinc oxide is a type of wide band gap semiconductor with a direct band gap of approximately 3.37 eV. It is used in ultraviolet light emitting diodes (LEDs) and piezoelectric devices [1][2]. Zinc oxide is also seen in gas sensors and solar cells [3][4] . Zinc oxide is extensively produced due to its unique combination of mechanical, electrical, and optical properties, including high transparency, wide band gap, and strong room-temperature luminescence. However, zinc oxide also has drawbacks. For example, low carrier mobility, low stability and relatively expensive compared to silicon. Silicon was the most developed semiconductor. It is a first generation semiconductor and was found in 1824. However, silicon's semiconductor properties were not found until the early 20th century. Silicon is also widely used for reasons like good carrier mobility, abundant and it's easy to be doped. Despite those advantages, silicon has limitations such as low breakdown voltage, indirect band gap and low thermal conductivity. Silicon is often used as MOSFETs, integrated circuits and solar cells [5]. The smallest silicon transistor technology has advanced to the 5 nanometer (nm) and more advanced nodes enabled by extreme ultraviolet (EUV) lithography [6]. This paper compares zinc oxide (ZnO) and silicon (Si) in terms of their physical properties, processing technologies, and potential applications. The author first analyzes the similarities and differences between zinc oxide and silicon. The author will then explore different applications of zinc oxide and silicon to find out the reason why this material is used. The paper provides the readers with the advantages and limitations of zinc oxide and silicon and also provides a scientific basis for the selection of semiconductor materials. The paper will offer research directions and inspiration for subsequent researchers in the field of materials science and electronic engineering. In conclusion, this paper provides readers with a comprehensive understanding of the roles, advantages, and limitations of zinc oxide and silicon in electronics, offering valuable insights for material selection in various applications.

2. Use and Comparison of Semiconductors

Scholars are actively exploring the applications of semiconductors. While silicon has a mature processing technology and is used in almost all electronics, the field of zinc oxide as a semiconductor remains less explored. In 2008, Qin Yong, Wang Xudong and Wang Zhong Lin used zinc oxide as a, arterial of piezoelectric device [3]. In 2015, researchers built a ultraviolet light-emitting diode based on zinc oxide [1]. In the same year, scholars successfully achieved a light-controlling, flexible and transparent ethanol gas sensor on wearable device using zinc oxide [4]. In 2023, researchers have built a zinc oxide based solar cell with a relatively high efficiency [7] [8]. Most of those applications are hard to achieve using silicon because zinc oxide's unique properties.

2.1 Use of silicon

Silicon is the most widely used semiconductor in electronics. In MOSFET applications, silicon's relatively high carrier mobility (electron mobility of 1350cm2/V.s and hole mobility of 480cm2/V.s at 1 atm and 300K) allows for faster switching frequencies compared to many other semiconductors.The electron mobility of pure silicon under 1 atm and 300K is 1350cm2/V.s and the hole mobility is 480cm2/V.s. Zinc oxide has a carrier mobility that is way lower than silicon. Silicon can easily be oxidized to form silicon dioxide. It is an insulator and it can be the dielectric coating of the MOSFET. What's more, silicon occupies 27.72% of the Earth and it is abundant. It is also easy to be doped into n-type and p-type semiconductors. This is the reason why silicon is cheaper than most semiconductors, including zinc oxide. Although zinc oxide is the fourth most common metal on Earth, its abundance is a lot less than silicon. Most zinc oxides are naturally n-type. It is hard and expensive to dope zinc oxide into a p-type semiconductor. Silicon is used in MOSFETs for most cases because of the properties above. It is also the reason for silicon to be widely used in integrated circuits.

2.2 Use of Zinc Oxide

2.2.1 UV LEDs (Ultraviolet Light-emitting Diodes)

Zinc oxide can be used as ultraviolet light emitting diodes. It is used because it has a wide and direct band gap of approximately 3.37 eV. A direct band gap means there is no change in momentum when an electron jumps between the conduction band and the valence band. When a material has a direct band gap, a photon will be emitted when the electron jumps from the conduction band to the valence band. On the contrary, when a semiconductor has an indirect band gap and an electron moves from the conduction band to the valence band, the energy will be released as heat. In 2015, a scholar found the doping concentration of p-type zinc oxide is 6.0×1016 cm-1 and the n-type magnesium oxide is used, an ultraviolet light emitting diode can be made as shown in Fig. 1 [1]. However, when it comes to silicon, the energy was emitted as heat because of the indirect band gap, as shown in Table 1. This makes silicon impossible for light emitting diodes. It also heats silicon and it may break when it works for a long time.

Table 1. Comparison between silicon (Si) and Zinc oxide (ZnO)

	Silicon (Si)	Zinc oxide (ZnO)
Band gap	1.1 eV; indirect	3.37 eV; direct

Fig. 1 Photograph of an operating ZnO UV laser diode and the corresponding device structure [1].

2.2.2 Piezoelectric devices

Zinc oxide is commonly used in piezoelectric devices. Examples of piezoelectric devices are piezoelectric sensors and actuators. In 1880, Pierre and Jacques Curie brothers discovered the piezoelectric effect. They found that when mechanical stress is applied to a piezoelectric material, there is a shift of charge. When there is an electric potential applied to the material, the material will experience a mechanical deformation. Common examples of piezoelectric materials include quartz, barium titanate, and zinc oxide. With the stress from body movements and winds, the piezoelectricity in textile fibers coated in zinc oxide is proven to be capable of fabricating "self powered nanosystems" [2][3]. Zinc oxide's suitability for piezoelectric devices stems not only from its piezoelectric properties but also from its relatively high mechanical strength. This property makes zinc oxide more durable. Although quartz (silicon dioxide) is also a piezoelectric material, its mechanical strength is a lot weaker than zinc oxide. Also, zinc oxide can be synthesized into different structures and it's relatively cheap. However, quartz with a relatively high purity requires a strict process and is relatively more expensive. Zinc oxide has a higher piezoelectric coefficient. This represents a greater voltage generation per unit of applied mechanical stress. The constitutive equation of the direct piezoelectric effect is [7]:

$$D = dT + \epsilon E \tag{1}$$

Where D is electrical displacement, d is the piezoelectric coefficient, T is stress, ε is permittivity of the material, and E is electric field.

2.2.3 Gas sensors

Zinc oxides are used in gas sensors. Gas sensors detect specific gases and trigger alarms when their concentration reaches a certain threshold, such as in the case of methane. As a semiconductor, zinc oxide's electrical conductivity can be easily changed by adsorbing gas molecules. The presence of a gas can create electron depletion or electron donation. After that, the resistance or current will change. The circuit will detect the change and will send the signal to an actuator. Zinc oxide is sensitive to various gases, which makes it suitable for a gas sensor. Gas sensors are often used in wearable electronic devices, which means they need to be flexible and transparent, they also need to be able to work under room temperatures. According to researchers, hexagonal wurtzite zinc oxide can be used for the gas sensor [4]. Unlike silicon, ZnO can perform such tasks. In 2015, researchers developed a light-controlling, flexible, transparent ethanol gas sensor that operates at room temperature using ZnO nanoparticles as shown in Fig. 2 [4]. Silicon cannot be transparent and is not easy to bend. The current and resistance will not change significantly when there's a high concentration of certain gas. All these properties make silicon impossible for making gas sensors.

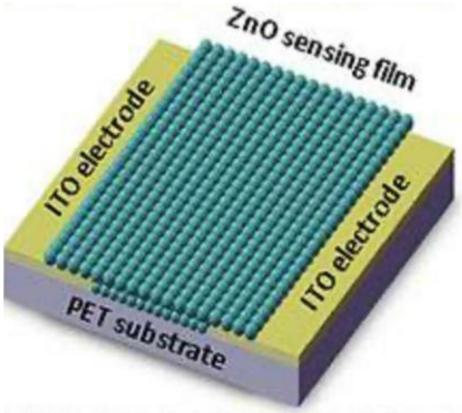

Fig. 2 Flexible gas sensor based on ZnO nanorods [4].

2.2.4 Solar cells

Zinc oxide is suitable for solar cells. With a band gap of approximately 3.37 eV, ZnO can efficiently absorb ultraviolet (UV) light, making it suitable for use in tandem solar cells - a type of multi-junction solar cell where different materials absorb different wavelength regions of sunlight. By using ZnO nanopins with graded refractive index characteristics as the anti-reflection layer, the efficiency of GaInP/GaAs/Ge solar cells was significantly improved, and the efficiency was increased by 45.8% under 100 times sunlight [5]. Although silicon can also be used as solar cells, it is used in a different way. In 2023, the efficiency of a silicon heterojunction solar cell has reached 25.94% with plating copper electrodes and double sided indium based transparent electrodes [8]. With an undoped SnOx front transparent electrode, they can also achieve a high efficiency of 24.91% [8]. Silicon heterojunction (SHJ) solar cells are an advanced technology in the domain of photovoltaics. There is a thin layer of crystalline silicon amorphous (not crystalline) with amorphous silicon layers on either side, creating a heterojunction. A SHJ solar cell can absorb light effectively and it can also provide a higher output voltage.

2.2.5 Other applications

Except for the uses of zinc oxide mentioned above, it is also used for ink in inkjet printer. In 2024, researchers utilized zinc oxide ink for inkjet printer ink to fabricate a thin film through "electrohydrodynamic printing" [9]. The absorbance was improved by two times at 360 nm wavelength and the electrical conductivity was improved by up to 40% compared to the spin-coated films [9]. Zinc oxide is proved to be possible for future nanoelectromechanical resonant accelerometer used for inertial navigation, tilt measurement, and geophysical measurements [10]. The absolute sensitivity of the zinc oxide based accelerometer was 16.818 kHz/g, the bias instability is 13.13 μg at 1.2 s integration time, and the bandwidth is from 4.78 to 29.64 kHz [10]. The design and fabrication of the zinc oxide nano-accelerometer is shown in Fig. 3.

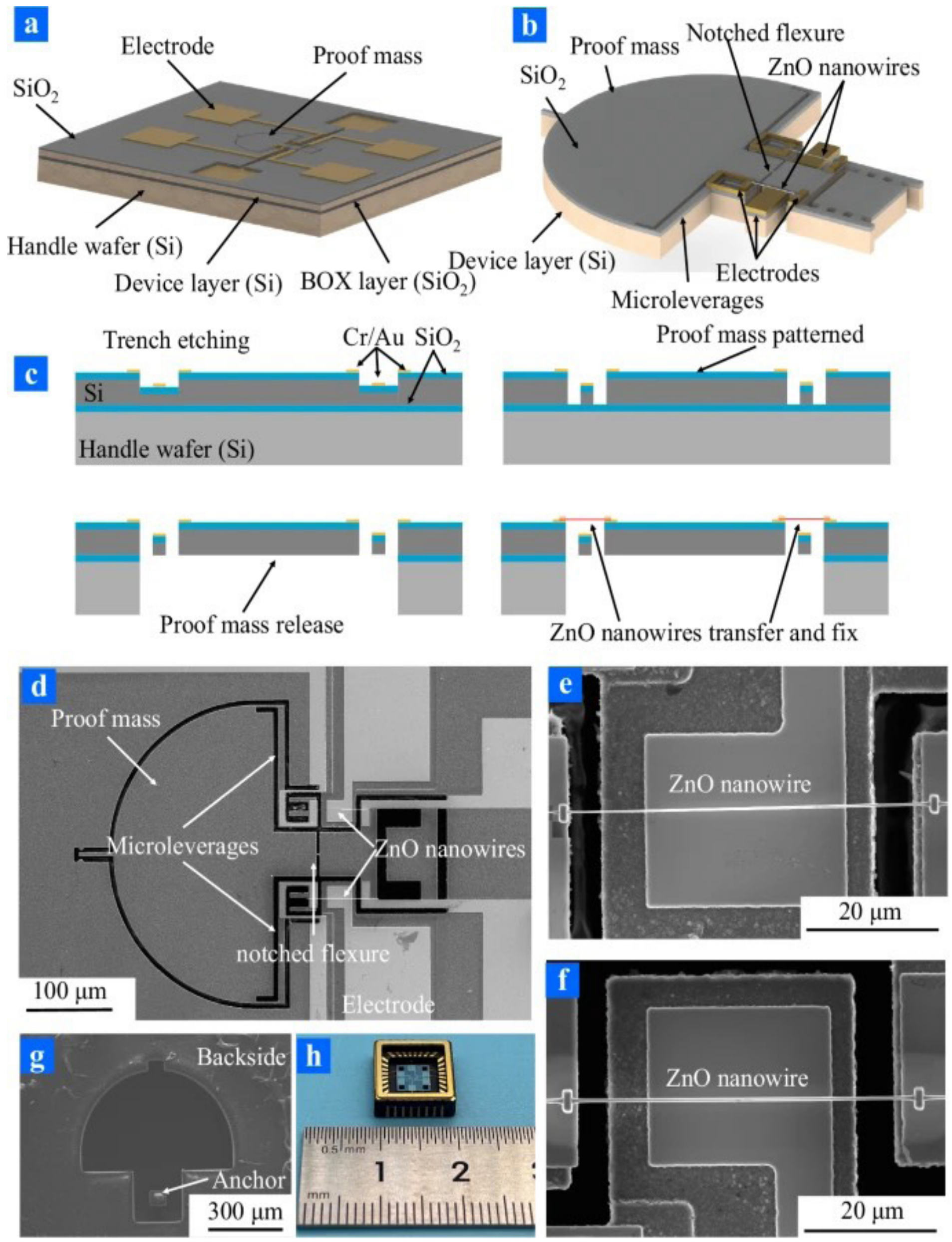

Fig. 3 ZnO resonant nano-accelerometers [10].

3. Conclusion

Zinc oxide and silicon are both crucial in electronics due to their unique properties: zinc oxide offers excellent stability at high temperatures and piezoelectric characteristics, while silicon provides high carrier mobility and ease of integration into complex circuits. Zinc oxide and silicon have different uses. It makes it impossible to replace one with another. For example, zinc oxides are used when stability at high temperatures is required. It has good optical properties and is a piezoelectric material. However, zinc oxide is not widely used in integrated circuits because of its lack of malleability and ductility. On the other hand, silicon is the foundation of modern electronics, it has relatively high carrier mobility, is cheap and easy to produce, and its oxide can also be used as a dielectric coating. However, it is unable to work under high temperatures and it's also easy to get hot because of its indirect band gap. Although zinc oxide is applied in electronics widely, it still has a huge potential. For example, zinc oxide has photocatalytic properties and can be used as a photocatalyst, this allows zinc oxide to be used in environmental and health applications, such as the purification of water and antibacterial coatings. In conclusion, zinc oxide and silicon occupy irreplaceable roles in their respective fields: zinc oxide excels in high-temperature applications, piezoelectric devices, and optoelectronics, while silicon remains the cornerstone of integrated circuits and traditional semiconductor devices.

References

[1]Liu, X. Y., et al. Ultraviolet lasers realized via electrostatic doping method. Scientific Reports, 2015, 5: 13641.

[2]Keim, B. Piezoelectric nanowires turn fabric into power source. Wired News, 2008, February 13.

[3]Qin, Y., Wang, X., and Wang, Z. L. Microfibre-nanowire hybrid structure for energy scavenging. Nature, 2008, 451(7180): 809–813.

[4]Zheng, Z. Q., et al. Light-controlling, flexible and transparent ethanol gas sensor based on ZnO nanoparticles for wearable devices. Scientific Reports, 2015, 5: 11070.

[5]Yeh, L. K., et al. Exceptionally omnidirectional broadband light harvesting scheme for multi-junction concentrator solar cells achieved via ZnO nanoneedles. Scientific Reports, 2016, 6: 39134.

[6]Hiramoto, T. Five nanometre CMOS technology. Nature Electronics, 2019, 2(10): 557–558.

[7]Jain, A., et al. Dielectric and piezoelectric properties of PVDF/PZT composites: A review. Polymer Engineering & Science, 2015, 55(7): 1589–1616.

[8]Yu, C., et al. Silicon solar cell with undoped tin oxide transparent electrode. Nature Energy, 2023, 8(11): 1119–1125.

[9]Esa, Z., Nauman, M. M., Ullah, M., et al. Compatibility and performance study of electrohydrodynamic printing using zinc oxide inkjet ink. Scientific Reports, 2024, 14: 16813.

[10]Xu, P., Wang, D., He, J., et al. A zinc oxide resonant nano-accelerometer with ultra-high sensitivity. Nature Communications, 2024, 15: 4651.