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Beta-Ga_2O_3 power semiconductor: material properties, doping and devices

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Abstract:

Doping and heterojunction engineering are essential to modern semiconductor technologies, enabling them to have impressive performances. N-type and P-type doping introduce electrons and holes into semiconductor crystals, which are the basis for many electronic devices. Over the years,researchers have achieved precise control of doping in common materials like silicon, but new challenges have emerged with novel materials and nanoscale devices. For instance, some wide-bandgap materials show intrinsic resistance to being doped. At the same time heterojunctions, interfaces between different semiconductor materials, have revolutionized efficiently. The purpose of this paper is to synthesize recent advances and persisting challenges in n-type doping, p-type doping, and semiconductor heterojunctions. Highlighting how improved doping techniques and clever material combinations are addressing these challenges, and providing suggestions for further research. The main conclusion is that while enormous progress has been made -from stabilizing n-type doping in organic films to designing lattice-matched heterostructures for minimal defectsfurther innovation in doping methods remains crucial.

Keywords: Beta-Ga_2O_3; doping; heterojunction.

1. Introduction

The global shift towards cleaner energy and transportation system have been overwhelmingly increasing in the past few decades. The rapid growth of electric vehicles exemplifies this transition: in 2023, worldwide electric car sales surged by 35% to nearly 14 million units, bringing the global EV fleet to about 40 million [1]. As more sectors start electrifying, an even larger share of electricity flows through power electronic converters that manage, convert, and control electrical energy. Recent “Hitachi energy” estimates that over 70% of electronics are powered by Power electronics, and this number is only expected to increase [2]. This therefore makes the efficiency of power electronics particularly leveraging when for reducing carbon emissions and saving on costs. Some semiconductor materials such as silicon carbide and gallium nitride have already begun replacing silicon in many electrical industries [3]. The next best option are ultrawide bandgap semiconductors with bandgap energies much greater than the 3.4 eV of GaN or 3.2 eV of SiC [4].

Ga_2O_3 in its stable Beta phase has garnered intense

interest as a key ultrawide bandgap semiconductor, it offers a bandgap of 4 eV which can sustaina higher critical field and hence a higher blocking voltage can be achieved at a smaller resistance and power electronic dimension. This is significantly higher than GaN or SiC making it up to 4 times higher Baliga's figure of merit than GaN or SiC. This means that a beta-Ga_2O_3 devices could block a even higher voltage with a thiner, lower esistance layer than GaN or SiC, enabling lower conduction losses and more compact devices. Furthermore, Ga_2O_3 can be obtained safely and easily. The main methods of preparation being laser molecular beam epitaxial (L-MBE), thermal annealing method, chemical vapor deposition (CVD), metal-organic chemical vapor deposition (MOCVD), radio frequency magnetron sputtering method, thermal evaporation method, and so on [5]. The scalability and substrate availability suggest that Beta-Ga_2O_3 devices could be produced at relative low costs and high volumes which is an important factor for industrialization.

Despite these compelling advantages, Beta-Ga_2O_3 currently faces several challenges before it can realize its full potential in power electronics. A primary concern is its poor thermal conductivity, it conducts much less effectively than SiC or GaN. This low thermal conductivity can lead to overheating of devices, potentially limiting their performance. Thermal management solutions like advanced cooling are being investigated as a result [6].

Another major challenge, and the focus of this paper, is the difficulty in achieving p-type doping in beta-Ga_2O_3. While n-type (electron) conductivity in beta-Ga_2O_3 is easily obtained there is no evidence or report stating that p-type doping has been achieve. This has been a recurring issue because most efficient power semiconductor designs require both type n and p regions. In beta-Ga_2O_3, the valence band structures, being relatively flat which lead to large effective masses for holes and making it difficult to create shallow acceptor levels [7]. Thus, if one introduces acceptor impurities, the holes cannot move freely leading to p-type beta-Ga_2O_3 virtually impossible under normal circumstances. As a consequence, beta-Ga_2O_3 researched has mainly been focused on unipolar devices (using only n-type material) [8]. However, the absence of a hole-conducting layer is considered the most serious limitation for beta. Ga_2O_3 device performance. For instance, in high-voltage diodes, a p-n function is normally used to spread the electric field and achieve a high breakdown voltage, but for beta-Ga_2O_3 is not possible thus pushing devices to their theoretical limits.

To adress the p-type doping problem, researchers are exploring innovative solutions. One approach is to form heterojunctions between n-type Ga_2O_3 and other compatible p-type semiconductors [8], using a different material to supply the "holes". These heterojunction devices have shown significant improvements, such as higher breakdown voltages. The trade-offs however, include the potential lattice missmatch and substrate oxidation which could limit performance. Although it has its trade-offs heterojunctions still is currently the most promising way to realize bipolar-style Ga_2O_3 devices until p-doping is achieved. This paper aims to address the current approaches to enabling bipolar devices in beta-Ga_2O_3, focusing on n-type and p-type doping as well as heterojunction designs. We begin by analyzing the known n-type dopants and their incorporation challenges. Next, we examine why p-type doping in beta-Ga_2O_3 is so difficult and summarize promising theoretical approaches. Finally, we review heterojunction solutions that bypass the challenges faced by p-type doping. By comparing the strengths and limitations of each stratergies, this paper will highlight key challenges and suggest further improvements and research.

2. Case

2.1 N-type doping in beta-Ga2O3

In its pure form, beta-Ga_2O_3 is typically an n-type semiconductor, meaning it has an excess of electrons available for conduction. N-type doping is achieved by introducing impurity atoms that have more valence electrons than gallium, such as tin, silicon and germanium. These dopants substitute for Ga^{3+} in the lattice and donate an extra electron to the conduction, thus increasing conductivity.

2.2 P-type doping in beta-Ga2O3

In contrast to n-type doping, to achieve p-type doping in beta-Ga_2O_3 has been proven to be significantly more difficult. P-type doping requires introducing acceptor dopants that have fewer valence electrons than gallium or introducing impurities to create "holes" (vacancies in the electron structure). Potential acceptors for Ga_2O_3 include magnesium, zinc and beryllium which could substitute for Ga^{3+} (each having 2+ in the lattice, potentially accepting an electron and leaving a whole) or nitrogen which could substitute for oxygen (since it has one fewer valence electron than oxygen). The fundamental issue is that any holes that form in Ga_2O_3 are not stable in the valence band- they become trapped in localized states or require too much energy to be activated. Therefore, as for now there are no viable p-type Ga_2O_3 semiconductors and remains a challenge.

2.3 Heterojunctions with compatible semiconductors

Given the difficulties with p-type Ga_2O_3, scientists have

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turned to heterojunctions as an alternative. A heterojunction is a junction formed between two different semiconductor materials. In the context of Ga_2O_3 power devices, this typically means paring n-type Ga_2O_3 with a p-type semiconductor that has a reasonably wide bandgap and compatible lattice and thermal properties. This p-type semiconductor provides the hole that the Ga_2O_3 lacks, allowing for diode structures that mimic a p-type doping.

3. Analysis & challenge

3.1 N-doping

N-type beta-Ga_2O_3 is typically doped with group-IV donors (Si, Sn, Ge), which theory predicts to be shallow in energy [9]. Ge and Sn doping were investigated in (001) beta-Ga_2O_3 using plasma assisted molecular beam epitaxy [10]. They found that Ge incorporation is strongly temperature dependent, saturating above 700 C whereas Sn incorporation is not as near temperature dependent. As a result to achieve carrier concentrations from 10^17 to 10^20 cm^{-3} , Ge-doped films must be grown at ≤650 °C, while Sn-doped films can use higher temperatures [10]. It has been investigated that higher growth temperatures yield smoother surfaces, thus Sn-doped films (grown hot) are smoother than Ge-doped ones. The trade off is that Ge allows very high doping levels but with rougher surfaces, and Sn yields smoother surfaces at the cost of needing heavier Sn flux. Measured room-temperature electron mobilites in (001) beta-Ga_2O_3 were around 25 cm^3/V reported similar concentrations. This suggests that material quality also affects transport in n-type beta-Ga_2O_3.

Another critical issue is dopant incorporation profiles, significant doping “delays” for Ge were shown to exist. Such Ge incorporation delay makes it difficult to create abrupt junctions. Thus, many techniques were used to address this issue: introducing a brief Ge pre-flow during Ga shutter closing reduced the delay, and similarly, growing a thick undoped beta-Ga_2O_3 buffer before Ge doping eliminated the delay almost entirely. The tweaks made suggest that roughness strongly affects Ge uptake. Overall, controlling n-type doping in beta-Ga_2O_3 requires optimizing growth temperature and sequence for each dopant.

3.2 P-doping

By contrast, p-type doping in beta-Ga_2O_3 remains a critical unsolved problem. As mentioned in previous work, fabricating p-type beta-Ga_2O_3 with shallow acceptors is vital for devices but has not yet been achieved. Conventional acceptors (Mg, N, Zn, etc …) introduce very deep levels so that holes are not thermally activated at room temperature [11]. One major hurdle is compensation by native donors: oxygen vacancies for easily and act as n-type donorns, counteracting any p-type dopants. Other studies show that this compensation can be mitigated by co-doping strategies. In the same paper mentioned, co-doping dramatically lowers the acceptor ionisation energy, and at the same time these co-dopants also raise the formation energy of O vacancies, because metals with p-orbitals hinder vacancy formation. In other words, co-doping simustaneosly produces shallow acceptors and suppresses compensating donors, thus conclude that (Mg,N) or (Zn,N) co-doping might be a potential way to achieve an effective p-type beta-Ga_2O_3.

Despite these promising predictions, experimental realization is still pending. No studies to date have clearly demonstrated robust p-type beta-Ga_2O_3 with appreciable hole concentration. In practice, attempts at N doping or Mg implantation have yielded only semi-insulating or compensated material. Thus, the main challenges are; finding a dopant or co-dopant that truly produces a shallow acceptor, and growing the material in conditions that avoid self-compensation. Additional difficulties include lattice strain and defect formation with heavy co-doping, and maintaining crystal quality. Given the extreme difficulty, researchers often turn to heterojunctions as an alternative.

3.3 Heterojunctions

Heterojunctions between beta-Ga_2O_3 and other semiconductors provide a way to realize p-n devices without p-type Ga_2O_3. In these structures, n-type beta-Ga_2O_3 is combined with a different p-type or wide-bandgap material to form a junction. Common pairings include p-NiO/n-Ga_2O_3 and p-Cu2O/n–Ga_2O_3. Nickel oxide is a p-type wide-bandgap semiconductor and forms a type-II heterojunction with Ga_2O_3, Cuprous oxide (Cu_2O) which is a lower bandgap p-type oxide can also be paired with Ga_2O_3 and has a more favourable band alignment than nickel oxide [8].

Studies of NiO/Ga_2O_3 heterojunctions have yielded record-breaking device performance. For example, vertical NiO/beta-Ga_2O_3 rectifiers with breakdown voltages exceeding 8kW, nearly independent of temperature until up to 600K. These devices achieved an on-off ratio of over 10^10, far outperforming comparable Ga_2O_3 Schottky diodes. Similarly, Ga_2O_3/NiO and Ga_2O_3/Cu2O junctions were fabricated into ITO glass and it was discovered that a strong rectification existed meaning that under the illumination the Ga_2O_3/Cu_2O cell gave an open-circuit voltage of roughly 0.94V, while Ga_2O_3/NiO yielded roughly 0.22V. The higher voltage for Ga_2O_3/Cu_2O is explained by its smaller conduction-band offset (a more favourable band arrangement). These heterojunctions showed that Ga_2O_3 can serve as an electron-transport layer while the p-oxide

provides holes and creating bipolar behaviour.
However, heterojunction devices face their own challenges as interface wuality and band alignment are critical. The Ga_2O_3/NiO heterojunction typically has a large valence-band offset, which can impede hole injection whereas Ga_2O_3/Cu_2O has only roughly a 0.94V bandgap for holes, limiting breakdown. Unusual large diode ideality factors were noted by previous research which suggests non-ideal interfaces or recombination at the junction. In practice, fabricating high-qualty interfaces often requires specialized methods. Scalability can be an issue and lattice or thermal missmatch may induce defects under high fields. Moreover, each heterostructure sacrifices some of the Ga_2O_3 properties like replacing instrict Ga_2O_3 with polycrystalline NiO means loosing transparency or adding processing complexity. Despite these issues, heterojunctions are the only demonstrated route to robust Ga_2O_3-based p-n diodes.

4. Summary and Suggestion

Table 1. Three Scheme comparing

Method	Progress	Challenge	Suggestion
N-type doping	High donor activation rate (around 100%)	Maintaining low resistance and high breakdown; growth-temperature trade offs	Use just enough donors and spread them smoothly through the crystal so you keep low resistance and high voltage strength
P-type doping	Shallow acceptor predicted (<0.2eV)	No reproducible room-temperture hole conduction; strong self-compensation	Experimentally validate co-doping under O-rich growth and measure hole density
Heterojunctions	Proven p-n rectifiers showing multi-kV blocking and photovoltaic response	Interface traps, band-offset mismatch, and scalability of fabrication	Adapt process to faster, factory style coating methods

3 types application process of beta-Ga_2O_3 is concluded and shown in Table. 1. N-type doping in beta-Ga_2O_3 has seen significant advancements, but new frontiers pose challenges. Careful management of doping levels is crucial because excessive donor concentrations can introduce defects or reduce electron mobility. To maximise device performance, researchers should optimize doping processes and explore new dopant elements or techniques that could further enhance n-doping without compromising material quality.
P-type doping in beta-Ga_2O_3 remains an unsolved challenge. Attempts to introduce typical acceptor impurities (such as Mg, Zn, or N) have not produced a viable p-type material, because these dopants create deep acceptor levels with activation energies over 1eV. Additionally, the valence band structure of Ga_2O_3 leads to a large effective hole mass and low mobility, and holes tend to localize instead of forming mobile charge carriers. As a result, no stable p-type conductivity has been demonstrated to date. Researchers have explored strategies like co-doping and extreme doping conditions, but without success.
Heterojunctions are an alternative to the absence of p-type doping, by combining an n-type beta-Ga_2O_3 with an complimentary p-type material (or another wide-bandgap structure) researchers have created functional devices. For example, p-NiO/n-Ga_2O_3 heterojunction diodes exhibit on low resistance and high reverse blocking voltages effectively achieving diode behaviour without p-Ga_2O_3. The main challenge for these devices is ensuring high-quality interfaces between materials, thus continued research is sought to try and refine interface engineering and try out new material combinations.

5. Conclusion

This paper explored how doping strategies and heterojunction engineering can unlock the potential of beta-Ga_2O_3 in high power-electronics. The progress in achieving reliable n-type doping, the ongoing quest of achieving p-type doping, and the development of heterojunctions that compensate for beta-Ga_2O_3 doping limitations were reviewed. The key insights are that p-type doping remains largely impractical due to fundamental material constraints. To try and fix this, heterojunctions have emerged as an effective solution, enabling functioning diodes without the need for p-doping. While challenges still remain, particularly in achieving stable p-type conductivity, the path forward lies in the continued refinement of doping techniques and het-

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erojunction combinations. Beta-Ga_2O_3 has demonstrated strong potential in high-power and high-voltage electronics and with further development it might become fundamental to future energy electronics.

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