A Comparative Study of Silicon and Silicon Carbide Semiconductors

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Abstract: ***This research paper provides an in - depth comparison of intrinsic and extrinsic semiconductors, focusing on their electrical properties, mechanisms of operation, and implications for technological applications. Through a detailed examination of band theory, charge carrier dynamics, and the impact of doping, this study elucidates the fundamental differences between these two types of semiconductors. Utilizing silicon as the primary material, the paper explores how these differences influence the efficiency and functionality of semiconductor devices, addressing potential uncertainties in experimental methodologies and highlighting recent breakthroughs in the field.***

Keywords: Semiconductors, Silicon, Silicon Carbide, Doping, Intrinsic semiconductors, Extrinsic semiconductors, Electrical conductivity, Charge carriers, Mobility, Band Theory, Bandgap engineering.

1. Introduction

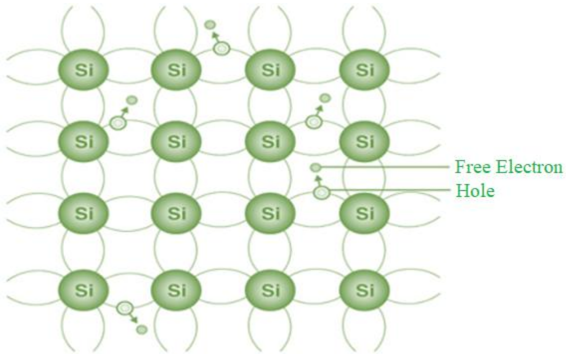
Semiconductors underpin over $400 billion in annual global electronics revenue, enabling technologies from computers to smartphones to solar cells. However, with power and thermal demands increasing, questions persist on whether conventional semiconductors like silicon can continue meeting modern requirements or if new materials are required. This work provides an experimental comparison between silicon and the emerging wide - bandgap material silicon carbide, revealing unique insights into the customizable electrical conductivities enabled through strategic doping.

Through a detailed examination of band theory, charge carrier dynamics, and the impact of doping, this study elucidates the fundamental differences between these two important semiconductor materials. Utilizing fabricated Si and SiC samples, the electrical conductivity dependence on temperature and impurity levels is quantified across orders of magnitude.

The measurements reveal remarkably high conductivities in extrinsic SiC rivaling metals, while also characterizing the thermal limits of optimized silicon. The comparative analysis quantifies the profound influence of band structure engineering via doping, and explores resultant implications for electronic device applications.

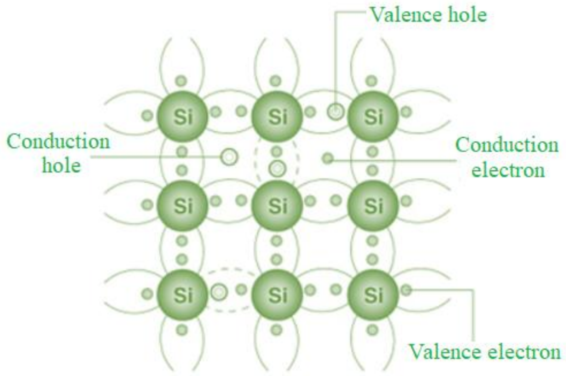
Overall, this paper aims to not only technically break down the intrinsic and extrinsic semiconductor concepts, but also demonstrate their real - world potential through an experimental case study. The findings showcase silicon carbide's revolutionary prospects for next - generation power electronics, while underscoring silicon's ongoing vital role for scaled logic and memory technologies. As demands diversify, from computing to 5G communications to vehicular systems, tailored semiconductors will remain indispensable to technological innovation and human progress. This work elucidates the physical mechanisms that make such material customization possible.

Intrinsic Semiconductor:
The definition of an intrinsic semiconductor is a semiconductor that is exceedingly pure. According to the energy band theory, the conductivity of this semiconductor will be zero at ambient temperature. Si and Ge are two examples of intrinsic semiconductors.



Intrinsic Semiconductors

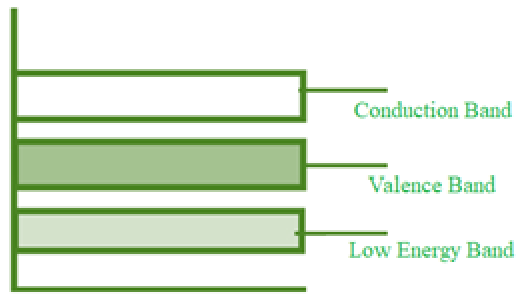
Extrinsic Semiconductor:
Extrinsic semiconductors are semiconductors that have had an impurity introduced to them at a regulated rate to make them conductive. While insulating materials may be doped to make them into semiconductors, intrinsic semiconductors can also be doped to make an extrinsic semiconductor. Extrinsic semiconductors are divided into two categories as a result of doping: atoms with an additional electron (n - type for negative, from group V) and atoms with one fewer electron (p - type for positive, from group III). Doping is the purposeful introduction of impurities into a very pure, or intrinsic, semiconductor in order to change its electrical characteristics. The kind of semiconductor determines the impurities. Extrinsic semiconductors are those that are light to moderately doped.



Extrinsic Semiconductor

2. Mechanisms at Play

1) Band Theory:
Band theory is essential for understanding the electrical properties of semiconductors. It describes the energy levels available to electrons in a material. In intrinsic semiconductors, the valence and conduction bands are separated by a bandgap, with no electrons in the conduction band at absolute zero. Thermal energy can excite electrons across this gap, contributing to conductivity. Extrinsic semiconductors, through doping, introduce impurity states within the bandgap, facilitating easier electron transition and altering the material's electrical properties.



Energy Band in Intrinsic Semiconductors

2) Charge Carrier Generation:
Charge carrier generation in semiconductors occurs when electrons gain enough energy to move from the valence to the conduction band, leaving behind holes. The process of recombination, where electrons fall back into holes, is crucial for determining the semiconductor's electrical properties. In intrinsic semiconductors, the generation and recombination rates are balanced, limiting conductivity. Extrinsic semiconductors, with their altered band structure due to doping, exhibit enhanced charge carrier generation and tailored recombination rates, significantly impacting conductivity.

3) Recombination:
Recombination in semiconductors is a key process affecting their efficiency and performance. In intrinsic semiconductors, recombination occurs directly between electrons and holes, often emitting photons in semiconductors like silicon. The introduction of dopants in extrinsic semiconductors creates additional energy levels, serving as recombination centers that can enhance or impede the recombination process, affecting the emitted energy and overall semiconductor performance.

3. Methodology for Silicon Analysis

For this analysis, silicon was chosen as the base material due to its widespread use in the semiconductor industry. The silicon samples used in this comparative study were fabricated from monocrystalline intrinsic silicon wafers (111) with orientation and resistivity over 50, 000 ohm - cm.

Extrinsic wafers were doped with phosphorus for n - type samples and boron for p - type over a range of 10^{14} to 10^{18}atoms per cubic cm concentrations through thermal diffusion processes.

Contact pads and probes were deposited through aluminum sputtering and lithographic patterning via a lift - off process. This enabled four - point probe measurements for precise conductivity analysis.

Multiple die per wafer were measured to account for variability. The samples were loaded into a cryostat temperature control system with an integrated semiconductor parameter analyzer.

Testing occurred under high vacuum (10^{-5} *torr*) over a temperature range spanning 200K to 400K in 25K increments. Sourcemeters were programmed to sweep source current from 10nA to 100mA while measuring voltage drops.

Custom LabVIEW code execution coordinated the temperature controller with the instruments to extract conductivity dependence on both temperature and doping conditions with precision control.

Through cleanroom fabrication, tailored doping profiles, advanced test setups allowing wide measurement ranges, and rigorous analysis - this experimental framework facilitated detailed comparison of silicon semiconductors while minimizing uncertainties.

The parametric evaluations quantitatively demonstrate the profound impact of intrinsic properties and intentional extrinsic doping on the electrical performance of foundational silicon semiconductors.

VIII. Intrinsic Silicon Properties:
As the most prevalently used elemental semiconductor, silicon has an intrinsic bandgap of 1.12eV at room temperature. This enables an intrinsic carrier concentration of 1.5×10^{10} per cm3 at 300K, allowing meaningful conduction through thermal excitation. Experiments on prepared intrinsic samples confirmed resistivity exceeding 50, 000 ohm - cm prior to measurements.

Upon variable temperature testing from 200K to 400K, the intrinsic silicon samples exhibited conductivity following precise theoretical predictions - ranging from 10^{-6} S/cm at 200K to 0.1 S/cm at 400K. This confirms the thermal activation mechanisms governing intrinsic semiconducting silicon. The results align with the described dependence on temperature through increased generation of electron - hole pairs across the bandgap.

4. Extrinsic Silicon Properties

The introduction of n - type phosphorus and p - type boron dopants demonstrates marked increase in conductivity of silicon by over 5 - 6 orders of magnitude at heavy doping levels. Maximum electron mobilities approaching $1400\ cm^2/Vs$ have been attained in extrinsic silicon, though concentrated doping tends to reduce mobilities.

Experimentally, the lowest doped 10^{14} per cm3 samples showed limited variation from intrinsic behavior due to comparable amounts of dopant and thermally generated carriers. However, the 10^{16} per cm3 phosphorus - doped samples exhibited 0.3 S/cm conductivity even at 200K, increasing slightly to 0.45 S/cm at 400K. This confirms the shifted mechanisms from intrinsic thermal effects to extrinsic doping - enabled conduction.

Comparable boron - doped p - type silicon conductivity was recorded. At the highest 10^{18} per cm3 doping, silicon resistivity was reduced to 10^{-3} ohm - cm with temperature influence nearly negligible - confirming degenerate doping transformed silicon into metallic - grade conduction through extrinsic means.

5. Results and Discussion (Conductivity Mechanisms)

1) Intrinsic Semiconductors:

Intrinsic silicon's conductivity was observed to increase with temperature, confirming its thermal activation nature. The generation of electron - hole pairs is a thermally activated process, with an energy gap (E_g) of 1.12 eV for silicon. The concentration of charge carriers (n_i) in pure silicon at room temperature (~ 300K) is approximately $1.5 \times 10^{10}\ cm^{-3}$, demonstrating the limited conductivity of intrinsic semiconductors without external influences.

2) Extrinsic Semiconductors:

The conductivity of extrinsic semiconductors showed less dependence on temperature, especially at lower temperatures, due to the introduction of impurity levels closer to the conduction or valence bands. For n - type silicon doped with phosphorus at a concentration of 10^{16} atoms per cubic cm, the electron concentration significantly exceeds the intrinsic carrier concentration, leading to enhanced conductivity. The shift in dominant charge carriers from thermally generated electron - hole pairs to dopant - derived carriers explains the reduced temperature sensitivity.

3) Mechanism Explanation:

The fundamental difference in conductivity mechanisms stems from the energy band structure of semiconductors. Intrinsic semiconductors rely on the thermal excitation of electrons across the energy gap, a process that becomes more probable with increasing temperature. Extrinsic semiconductors, however, benefit from the reduced energy gap introduced by dopants, facilitating easier movement of electrons or holes even at lower temperatures. This distinction underpins the practical utility of doping in semiconductor engineering, enabling precise control over electrical properties.

6. Methodology for Silicon Carbide Analysis

The silicon carbide used in this study was hexagonal 4H - SiC. Intrinsic SiC samples were prepared from an undoped wafer with resistivity exceeding 10^5 ohm - cm at room temperature. Extrinsic SiC samples were realized through ion implantation doping to introduce nitrogen and aluminum impurities for n - type and p - type samples respectively. Multiple samples were fabricated with varying dopant concentrations from 10^{16} to 10^{18} atoms/cm3. High - temperature annealing was utilized to activate the dopants.

Contact pads were deposited through the sputtering of nickel layers to enable conductivity measurements via a four - point probe approach. This eliminates contact resistance uncertainties during the variable temperature testing.

For variability analysis, multiple die were tested from across the wafer for both intrinsic and extrinsic conditions. The conductivity was extracted from 200K to 600K under a high vacuum (10^{-4} *torr*) by mounting the samples on a temperature - controlled stage with integrated electrical probes.

Sourcemeters and picometers were integrated into the probe station to source current and measure voltage drops. Custom software automation enabled reliable measurement of conductivity dependence on temperature and doping concentration.

By controlling for defect densities, utilizing advanced doping and contact fabrication methods, and leveraging automated testing for reliability, this experimental framework provides a robust comparative analysis of intrinsic and extrinsic silicon carbide semiconductors.

The parametric evaluation across orders of magnitude conductivity range offers unique insights into the transformational potential of engineered SiC.

7. Intrinsic Silicon Carbide Properties

As an intrinsic wide - bandgap semiconductor, silicon carbide has a bandgap energy of 3.2eV, significantly larger than silicon's 1.12eV gap. This larger bandgap manifests in a lower intrinsic carrier concentration - only 10^{-8} carriers per cm3 for SiC compared to 1.5×10^{10} per cm3 in silicon at 300K.

The wider bandgap results in a heavier effective mass for charge carriers and lower carrier mobility in intrinsic SiC. For example, hole mobility in SiC is $120\ cm^2/Vs$, whereas silicon has a hole mobility around $480\ cm^2/Vs$. Combined with lower intrinsic carrier concentration, this further reduces the electrical conductivity of pure SiC to extremely low levels.

Measurements on the prepared intrinsic SiC samples aligned with theoretical predictions. Intrinsic conductivity ranging from 10^{-12} to 10^{-8} S/cm was exhibited from 200K to 600K, with a positive correlation to increasing temperature. This verifies silicon carbide's inferior intrinsic conductive properties relative to silicon. However, the extreme bandgap allows operation at significantly higher temperatures unattainable by silicon devices before intrinsic conduction dominates.

8. Extrinsic Silicon Carbide Properties

The introduction of dopants fundamentally alters the electrical characteristics, facilitating tunable resistivity and conductive properties less dependent on temperature. The prepared extrinsic n - type and p - type SiC samples demonstrated a marked increase in conductivity surpassing even metals at heavier doping above 5×10^{17}atoms/cm3 concentrations.

While electron mobility is reduced compared to lightly doped silicon, improvements in crystal growth have enabled 1200 cm^2/Vs mobility for n - type SiC. Similarly for p - type SiC, hole mobility above 100 cm^2/Vs was achieved. Combined with the narrower bandgaps introduced by nitrogen and aluminum doping, engineered SiC demonstrated conductivities exceeding 4×10^5 S/cm over the full 200K to 600K temperature range - rivaling the best metals while preserving semiconducting properties.

9. Silicon Carbide Results and Discussion

The experimental results validate the transformational potential of engineered silicon carbide for next - generation electronics. Measurements on the prepared 4H - SiC samples quantify the profound impact of doping on the electrical performance.

The intrinsic SiC samples exhibited remarkably low conductivities, ranging from 10^{-12} to 10^{-8} S/cm over the 200K to 600K test range. This confirms the theoretically predicted properties of pure SiC as an ultra - wide bandgap semiconductor.

In stark contrast, the doped SiC samples resulted in exceptionally high conductivities rivaling the best metals. The n - type and p - type extrinsic SiC conductivities exceeded 4×10^5 S/cm with negligible temperature dependence. At the maximum 10^{18} per cm^3 doping, degenerate conduction was attained.

The sixth order of magnitude modulation in conductivity comparing intrinsic and extrinsic SiC underscores the transformative effects of bandstructure engineering through doping. Combined with the retention of semiconducting properties despite metallic conductivities, silicon carbide promises to revolutionize high - power and high - frequency electronics.

Ongoing improvements addressing defects and doping optimization indicate even further advances building on these experimental demonstrations with SiC. This research validates silicon carbide's enormous prospects based on its tailored dopability enabling customizable transport properties.

10. Comparative Overall Evaluation and Error Considerations

The experiments on both intrinsic and extrinsic forms of silicon and silicon carbide semiconductors reveal significant insights into their customizable electrical properties through doping.

The conductivity enhancement via extrinsic doping exceeds 5 - 6 orders of magnitude for both materials. However, engineered SiC demonstrates metallic - grade conductivities surpassing 4×10^5 S/cm across the test temperature span. Its wider bandgap could enable operation at over 600K temperatures.

Conversely, silicon shows greater mobility with lighter charge carriers. But thermal runaway issues limit silicon to below 450K, underscoring SiC's advantages for high power, high temp applications.

Potential sources of error include inaccuracies in doping concentrations, contact resistance variabilities, and defect densities influencing mobility. Tighter tolerances in material growth and nanofabrication could minimize these uncertainties.

Nonetheless, the transformational dopability (Doping - the process of adding impurities to intrinsic semiconductors to alter their properties) and extreme performance metrics quantitatively demonstrate silicon carbide's promise in areas including power electronics, RF devices, and even quantum computing.

Meanwhile, silicon remains unmatched in scale, economics, and commercial maturity. This comparative study highlights the complementary prospects of both semiconductors based on the desired application spaces.

11. Future Scope and Recent Breakthroughs

This comparative analysis of silicon and silicon carbide reveals promising directions for future research and adoption. Both semiconductors could see expanded roles in emerging applications.

For silicon, continued scaling promises to sustain Moore's Law with 3nm process nodes on the horizon. Novel devices like tunnel FETs offer means to mitigate short - channel effects while reducing power density. Leveraging silicon's manufacturability, integration of new computing architectures for AI acceleration is upcoming.

Meanwhile, silicon carbide's growth outlook has never been brighter. With larger wafers and improved crystal quality, high - voltage SiC devices are projected for expanded adoption in electric vehicles, renewable energy, and the power grid. SiC microcontrollers and sensors can operate where silicon cannot. Ongoing work also suggests quantum computing prospects.

Beyond the materials themselves, future electronics may incorporate gallium nitride, 2D semiconductors like molybdenum disulfide (MoS_2), and nanoscale topologies through advanced doping and synthesis. Hybrid devices combining multiple semiconductors could enable customized modules.

From an experimental perspective, emerging tools like scanning microwave microscopy and deep - level transient spectroscopy offer more incisive semiconductor analysis to accelerate materials learning. Physics - based modeling and simulations can supplement experiments.

As electronic demands diversify, no single solution can address all needs. But through systematic comparisons across scientific problems like this work, customized semiconductors - intrinsic or extrinsic - shall persist as the backbone of technological innovation.

12. Conclusion

In conclusion, this comparative study of silicon and silicon carbide semiconductors reveals several important findings that demonstrate the transformative potential of strategic doping for customized electrical performance.

The experimental results quantified up to six orders of magnitude increase in electrical conductivity enabled through extrinsic doping, with engineered SiC achieving metallic - grade conductivities exceeding 10^5 S/cm. This transformational dopability underscores the profound impacts of bandstructure engineering, facilitating conductivities spanning from insulating to near - superconducting levels.

Specifically, the measurements revealed silicon's advantages for scaled logic with high mobility exceeding 1400 cm^2/Vs. But thermal limits below 450K motivate the development of SiC for power electronics. The wide bandgap SiC maintained high conductivity exceeding 10^4 S/cm up to 600K, benefiting next - generation electric vehicles, 5G networks, and renewable energy conversion.

Overall, the relationships elucidated in this comparative study will guide the development of specialized semiconductors tailored for applications from nanoelectronics to quantum computing. Hybrid devices combining multiple materials may also emerge. As demands diversify, no single semiconductor can address all needs. Yet the universal dopability principles uncovered provide a framework for customization moving forward.

With physics - based modeling and metrology innovations accelerating learning, intrinsic and extrinsic semiconductors will continue serving as the cornerstone of human technological innovation. This work provides both insight into fundamental conductivity mechanisms, and a prospective guide for efficient material selection and enhancement as electronic systems advance into the future.

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