Chemical processing of silicon semiconductor materials and their physical fundamentals

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Abstract: Silicon remains the dominant semiconductor material in modern microelectronics due to its well-established processing technology and favorable physical properties. This paper investigates the chemical processing techniques applied to silicon and analyzes their fundamental physical mechanisms. Particular attention is given to wet and dry chemical etching, thermal oxidation, and doping processes, which play a critical role in surface morphology control and electrical property optimization. The influence of oxide layer thickness, surface states, and defect-induced recombination centers on carrier transport characteristics is discussed. The analysis demonstrates that precise control of chemical processing parameters significantly enhances device reliability and performance in MOS structures, integrated circuits, and photovoltaic applications.

Keywords: silicon, chemical processing, wet etching, thermal oxidation, doping, MOS structures, surface defects

Introduction. Modern electronics and microelectronics are fundamentally based on semiconductor materials. Among them, silicon (Si) is considered the most important material due to its favorable physical and chemical properties, natural abundance, and technological compatibility. Silicon-based devices are widely used in integrated circuits, transistors, solar cells, and various sensors. The reliability and performance of these devices largely depend on the quality and structural characteristics of the silicon surface.

Chemical processing of silicon is one of the key stages in semiconductor technology, encompassing surface cleaning, oxide layer formation, impurity incorporation, and microstructure patterning. Through chemical treatment methods, it becomes possible to control the electrical properties of silicon and precisely adjust device parameters. Therefore, the study and improvement of chemical processing techniques for silicon remain a highly relevant issue in the development of semiconductor technologies.

Literature Review. Issues related to the chemical processing of semiconductor materials, particularly silicon, have been extensively investigated in the scientific works of both local and international researchers. These studies analyze the crystal lattice of silicon, the energy gap between the valence band and the conduction band (band gap), as well as the influence of surface states and defects on electrical properties.

Scientific literature describes the main chemical processing techniques for silicon wafers, including wet chemical etching, dry chemical etching, and plasma-based processing methods. Researchers have explained the mechanisms of silicon oxide layer removal using mixtures of hydrofluoric acid (HF), nitric acid (HNO_3), and acetic acid (CH_3COOH) during wet chemical treatment. In this process, selective etching of silicon oxide and surface smoothness are emphasized as critical factors. Several studies consider silicon surface oxidation from the perspective of diffusion phenomena and reaction kinetics. During thermal oxidation, oxygen atoms diffuse into the silicon crystal lattice, forming a SiO_2 dielectric layer that directly affects the electrical strength and capacitive properties of semiconductor devices. In particular, the thickness and uniformity of the oxide layer in MOS (metal-oxide-semiconductor) structures are identified as decisive parameters.

In addition, the literature highlights impurity incorporation (doping) processes in silicon as being closely related to chemical treatment. The diffusion of boron (B), phosphorus (P), and arsenic (As) atoms leads to the formation of p-type and n-type conductivity, with changes in charge carrier concentration and mobility analyzed using physical models. Recent studies also focus on the atomic and molecular state of the silicon surface, surface energy, and adsorption phenomena. It is emphasized that surface defects generated during chemical processing may act as recombination centers, thereby reducing the efficiency and performance of semiconductor devices.

Overall, the literature review indicates that a thorough physical analysis and optimization of chemical processing techniques for silicon are of significant scientific and practical importance for the advancement of semiconductor technologies.

Method. Chemical processes are employed at nearly all technological stages in the fabrication of semiconductor devices. Chemical and electrochemical treatment processes can be classified into four main stages:

1. *Surface cleaning and stabilization*
2. *Surface polishing*
3. *Evaluation of the quality of the semiconductor material or the p-n junction*
4. *Coating the semiconductor surface with stabilizing, protective, and contact-forming materials*

In many chemical processes, chemical etching plays a crucial role in surface cleaning, removal of damaged surface layers, and the identification of subsurface and bulk defects in semiconductor materials. Based on the interaction mechanisms between the etchant and the semiconductor surface, chemical etching is a multistep dissolution process consisting of the following stages:

- Transport of etchant ions from the bulk solution to the semiconductor surface;
- Adsorption of etchant molecules on the semiconductor surface;
- Chemical interaction between the semiconductor surface and the adsorbed etchant molecules;
- Desorption of the reaction products from the semiconductor surface;
- Removal of reaction products from the surface into the bulk solution.

As a result of the etching process, the semiconductor surface is required to exhibit a smooth and uniform morphology. Chemical etching methods are generally classified into five types:

1. Isotropic etching - Characterized by equal etching rates in all crystallographic directions of a single crystal. This method is used to remove the damaged surface layer and to achieve surface polishing of the semiconductor material.

2. Anisotropic etching - Involves direction-dependent etching rates along different crystallographic orientations of the single crystal. This method is widely applied for metallographic and optical inspection of bulk and surface structural defects.

3. Selective etching - Exhibits different etching rates in various surface regions or along specific crystallographic orientations of the substrate. In selected etchants, layers with different chemical compositions are etched at different rates. This technique enables the visualization of crystal lattice mismatches, such as dislocations, localized defects, grain boundaries, and other structural imperfections.

4. Local etching - Refers to the removal of material from strictly defined and predetermined regions of the substrate surface. This method enables the formation of crystals with specific reliefs and well-defined geometries and facilitates the patterning of required microstructures. Both isotropic and anisotropic etchants are employed in local chemical etching processes.

5. Layer-by-layer etching - Applied after ion implantation, this technique removes successive thin layers from the semiconductor surface in a controlled manner. It is used to investigate impurity diffusion profiles, as well as the bulk and surface defects of epitaxial layers and substrates. In this method, polishing etchants with etching rates lower than 0.1 μm/min are typically employed.

Discussion. Etchants that allow continuous diffusion-controlled monitoring of the etching rate are commonly referred to as *polishing etchants*, while the corresponding process is known as *integral etching*. An increase in the viscosity of the etching solution, achieved by the addition of glycerin or polyhydric alcohols, significantly enhances its polishing capability. Higher viscosity slows down mass transport processes, leading to a more uniform dissolution of the semiconductor surface and improved surface smoothness.

The etching mechanism of semiconductor materials strongly depends on both the intrinsic properties of the material and the chemical composition of the etchant. In general, two principal etching mechanisms can be distinguished: electrical (electrochemical) and chemical mechanisms. In chemical etching, the dissolution process is governed primarily by chemical reaction kinetics rather than by electrical effects at the semiconductor surface.

The etching process follows the fundamental laws of chemical kinetics, including reaction rate dependence on temperature, concentration of reactive species, and diffusion rates. Under these conditions, charged surface states and surface potential variations play a negligible role in determining the overall etching rate. This behavior is particularly characteristic of purely chemical etching systems, where the rate-limiting step is either surface reaction or mass transport of etchant species.

Diffusion-controlled etching regimes are especially advantageous for achieving high-quality surface polishing. In such regimes, the etching rate is limited by the diffusion of reactive ions or molecules toward the semiconductor surface. This results in preferential smoothing of surface asperities, as protruding regions are etched more rapidly than recessed areas. Consequently, integral etching processes are widely employed for final surface preparation prior to critical fabrication steps such as oxidation, lithography, and epitaxial growth.

Furthermore, the choice of etching mechanism has a direct impact on surface morphology, defect revelation, and interface quality. Chemical etching is particularly effective for removing mechanically damaged layers and revealing crystallographic defects, while electrochemical etching may introduce additional surface inhomogeneities due to localized electric field effects. Therefore, for applications requiring atomically smooth surfaces and minimal defect density, chemically controlled polishing etchants are generally preferred.

Overall, the discussion confirms that careful optimization of etchant composition, viscosity, and diffusion conditions is essential for precise control of etching kinetics and surface quality. These factors play a critical role in ensuring the reproducibility and reliability of semiconductor device fabrication processes, especially in advanced silicon-based microelectronic technologies.

Conclusion. This article analyzed the chemical processing methods applied to silicon as a semiconductor material and their underlying physical principles. The results demonstrate that chemical treatment of the silicon surface plays a crucial role in controlling its structural state, electrical conductivity, and charge carrier properties. Chemical processing enables precise control over the thickness and uniformity of oxide layers as well as the concentration of surface defects.

Wet and dry chemical treatment methods, along with oxidation and doping processes, were identified as key factors determining the reliability and performance of semiconductor devices. In particular, the quality of the SiO_2 dielectric layer in MOS structures directly influences electrical strength and long-term operational stability. Reducing surface defects and recombination centers during chemical processing contributes to an increased charge carrier lifetime.

In conclusion, comprehensive investigation and optimization of silicon chemical processing techniques are essential for the development of high-quality and competitive semiconductor devices in modern microelectronics, integrated circuits, and solar energy applications.

References

1. Zaynabidinov, S. Z., Abdurakhmanov, B. M., Aliev, R., Olimov, L. O., Mukhtarov, E. Fabrication of polycrystalline silicon wafers from silicon powder. Geliotekhnika, no. 3, 2005, pp. 79-82.

2. Trakhtenberg, L. I., Melnikova, M. Ya. Synthesis, Structure, and Properties of Metal/Semiconductor-Containing Nanostructured Composites. Technosphere Publishing House, Moscow, 2016, 624 p.

3. Iversen, T.-G., Skotland, T., Sandvig, K. Endocytosis and intracellular transport of nanoparticles: Present knowledge and need for future studies. Nano Today, 2011, pp. 176-185.

4. Harbeke, G. (Ed.) Polycrystalline Semiconductors: Physical Properties and Applications. Translated from English. Mir Publishers, Moscow, 1989, 344 p.

5. Zaynabidinov, S., Sokhibova, Z. M., Nosirov, M. A method for determining the thermal conductivity of granulated silicon containing alkali metal atoms. The Way of Science: International Scientific Journal, 2022, no. 3 (97), pp. 15-17.

6. Zaynabidinov, S. Z., Sokhibova, Z. M., Abdurakhmanov, B. M., Ashurov, H. B., Adilov, M. M. Dependence of the electrical conductivity of granular semiconductors on grain size. Scientific Bulletin: Physical and Mathematical Research, 2021, vol. 3, issue 2, pp. 13-18.

7. Abdurakhmanov, B. M., Sokhibova, Z. M., Adilov, M. M., Ashurov, H. B. Determination of the specific thermoelectromotive force of granular silicon doped with alkali metals. Scientific Bulletin: Physical and Mathematical Research, 2021, vol. 3, issue 1, pp. 42-45.

8. Sokhibova, Z. M. Influence of potassium atoms on charge carrier drift in granular silicon. Universum: Technical Sciences, 2020, no. 9 (78), part 2, pp. 99-102.

9. Sokhibova, Z. M. Methods for measuring thermoelectric power and electrical conductivity of thermoelectric materials at high temperatures. Journal of Mechanical Engineering (Scientific and Technical Journal), 2022, no. 1 (Special Issue), pp. 132-136.

10. Sokhibova, Z. M. The role of granulated semiconductors in modern physics. International Scientific Journal “Global Science and Innovations 2019: Central Asia”, Nur-Sultan, Kazakhstan, September-October 2019, pp. 117-118.