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Original Research Article

Advantages of TMAH in the development of MEMS-based sensors

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ABSTRACT
The advancement of microelectromechanical systems (MEMS) has significantly transformed sensor technology by allowing the integration of mechanical and electronic components on a single chip. Among the various etchants used in MEMS device fabrication, tetramethylammonium hydroxide (TMAH) has gained prominence due to its unique properties and advantages. This paper explores the benefits of using TMAH as a wet etching technique in developing MEMS-based sensors, particularly for the fabrication of diaphragm structures essential for sensing applications. The TMAH solution provides high etch rates and excellent anisotropic etching capabilities, enabling the precise fabrication of the complex geometries required in MEMS technology. Furthermore, TMAH is compatible with complementary metal-oxide-semiconductor (CMOS) processes, which facilitates seamless integration with electronic circuits. Additionally, TMAH has low toxicity, enhancing safety during manufacturing processes and making it a preferable choice over other etchants like potassium hydroxide (KOH). Its ability to achieve smooth surface finishes contributes to improved sensor performance by minimizing noise and enhancing sensitivity. This paper also discusses TMAH's selectivity toward silicon dioxide and silicon nitride as masking materials, further increasing its utility in MEMS fabrication. Overall, TMAH represents a significant advancement in etching technology for MEMS-based sensors, promoting higher efficiency and performance across various applications.

1. Introduction

Microelectromechanical systems (MEMS) have impacted on various fields by merging mechanical elements with electronics at the microscale. This integration enables the development of highly sensitive, compact, and multifunctional devices such as accelerometers, pressure sensors, and flow sensors. Among the many etchants available, tetramethylammonium hydroxide (TMAH) has emerged as a preferred choice for etching silicon in MEMS fabrication [1-4].

TMAH is an organic base that offers several advantages over traditional etchants, such as potassium hydroxide (KOH), due to its unique properties. Its high etch rate, excellent anisotropy, compatibility with CMOS processes, low toxicity, and ability to produce smooth surface finishes make TMAH an ideal solution for MEMS fabrication [1], [7-9]. This paper examines the role of TMAH in enhancing the precision and efficiency of MEMS sensor fabrication, focusing on its application in creating diaphragm structures which is crucial for various MEMS-based sensors [3].

$$N(CH_3)_4^+Cl^- + KOH \rightarrow N(CH_3)_4^+OH^- + KCl$$

Materials Needed: Glass Container, Thermometer, Stirrer Hot Plate, The Condensor Top Breaker assembly located in pictured, TMAH Solution.

2. Properties of TMAH and its advantages in MEMS fabrication

Tetramethylammonium hydroxide (TMAH) is a widely used alkaline solution in MEMS fabrication. It is particularly favoured for its remarkable etching characteristics, including high etch rates and excellent anisotropic etching properties. These features are critical for defining sharp and precise structures required in MEMS technology. The key advantages of TMAH as an etchant include:

2.1 High etching rate

TMAH provides high etch rates when applied to silicon, making it suitable for the rapid etching of silicon wafers. The high etching rate enables shorter processing times and improved throughput in MEMS device fabrication, a crucial factor in industrial-scale production.

2.2 Anisotropic etching

Anisotropic etching refers to the ability of the etching process to remove material at different rates along different crystallographic directions. TMAH offers excellent anisotropic etching behaviour, which is essential for creating the precise geometries needed for MEMS devices. In particular, TMAH's anisotropic etching enables the fabrication of vertical sidewalls, a critical feature for creating diaphragm structures that are required in many MEMS sensors.

2.3 Compatibility with CMOS processes

One of the advantages of TMAH is its compatibility with complementary metal-oxide-semiconductor (CMOS) processes. CMOS technology is the backbone of modern integrated circuits, and its integration with MEMS devices enables the creation of highly compact and efficient systems. The ability to use TMAH for both mechanical and electronic fabrication steps in MEMS devices simplifies the manufacturing process and reduces production costs by avoiding the need for separate etching steps for the mechanical and electronic parts of the device.

2.4 Low toxicity and safety benefits

Unlike potassium hydroxide (KOH), which is highly toxic and caustic, TMAH is a significantly lower toxicity profile. This makes TMAH a safer alternative for both the environment and workers in the fabrication process. Its lower toxicity also reduces the potential for environmental harm, contributing to more sustainable MEMS manufacturing practices.

2.5 Smooth surface furnishes

TMAH etching results in smooth surface finishes as shown in fig.1 [1], which is essential for the performance of MEMS sensors. Surface roughness can introduce noise and reduce sensor sensitivity, affecting the overall accuracy of measurements. The smoothness achieved with TMAH etching helps to overcome these issues, improving the sensitivity and reliability of MEMS-based sensors.

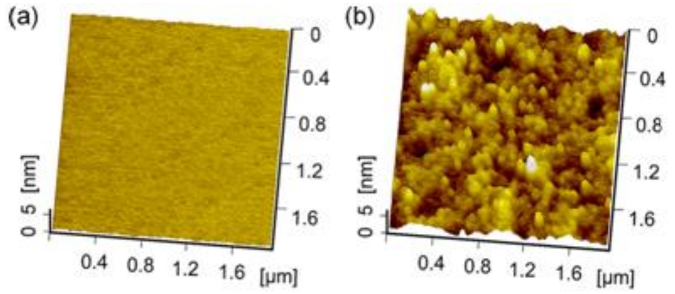

Figure 1: (a) Surface after TMAH etching; (b) Surface after KOH etching [1].

3. Application of TMAH in fabricating MEMS diaphragm structures

Diaphragm structures are crucial in MEMS sensors that detect pressure, acceleration, and force. These structures are usually made by etching thin silicon wafers to create a flexible membrane that can bend when exposed to external forces. The deformation is then translated into a measurable electrical signal, often through changes in capacitance, resistance, or piezoelectric properties.

TMAH has proven to be an excellent etchant for fabricating diaphragm structures due to its ability to create highly precise and well-defined geometries. The etching process allows for the selective removal of material from the silicon wafer to create the desired membrane thickness while maintaining the required mechanical properties of the diaphragm. Additionally, the anisotropic etching behaviour of TMAH allows for the creation of vertical sidewalls, which are critical for ensuring the structural integrity of the diaphragm.

By using TMAH for diaphragm fabrication, MEMS sensors benefit from improved mechanical performance, higher precision, and enhanced sensitivity, which are crucial for applications that require accurate and reliable measurements, such as pressure sensors, flow sensors, and accelerometers.

4. Bulk micromachining selectivity of TMAH

In MEMS fabrication, masking materials such as silicon dioxide (SiO_2) and silicon nitride (Si_3N_4) are often used to protect certain areas of the silicon wafer during the etching process. TMAH exhibits good selectivity toward these materials, meaning it etches silicon while leaving the masking layers intact. This selectivity is essential for creating complex MEMS structures with multiple layers and intricate designs [6].

TMAH's selectivity allows for precise patterning and the ability to fabricate sophisticated MEMS devices with different layers of material, each serving a distinct purpose. The use of SiO_2 and Si_3N_4 as etch masks ensures that the underlying silicon is etched only in the desired areas, allowing for the creation of highly detailed and functional MEMS devices [10]. Step by step procedure for bulk micromachining is shown in Figure 3.

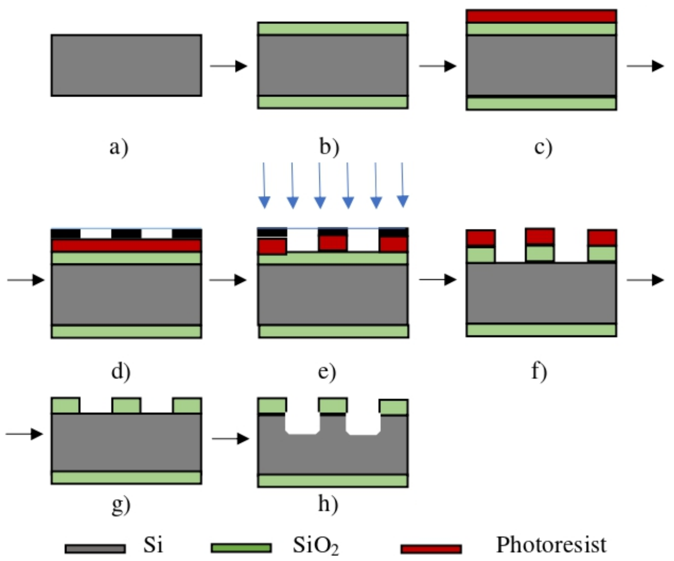

Figure 2: (a) Substrate; (b) Oxidation; (c); Photoresist Coating; (d) Masking; (e) U.V. Exposure and Develop; (f) Reactive Ion Etching; (g) Photoresist Removal; (h) Silicon etched using TMAH.

5. Comparison with other etchants (KOH vs. TMAH)

While TMAH has many advantages, it is important to compare it with other commonly used etchants, such as potassium hydroxide (KOH), to fully understand its strengths and limitations. KOH has been traditionally used for etching silicon in MEMS fabrication, but it presents several challenges compared to TMAH:

Toxicity: KOH is more toxic and caustic than TMAH, making it less suitable for environments where safety is a priority.

Etching Behavior: KOH etching can produce rougher surface finishes than TMAH [1] as shown in Figure 1, which may result in higher noise levels and reduced sensor sensitivity.

Anisotropy: Although KOH also exhibits anisotropic etching, TMAH generally offers better control over the etching process, especially when precise geometries and smooth surfaces are required.

Etch rate of Si{100} in surfactant added TMAH at high temperature [2]. Etching temperature is varied from 80 to 115°C, which is close to the boiling point of the etchant solution. Figure 3 [2] shows the temperature dependence etch rate of Si{100} in Triton-X-100 added 25 wt% TMAH. It is reported that the etching rate above 100 □ is increased 3 to 4 times that in 80 % solution. The effect of etching temperature on the etched surface roughness is presented in Figure 4 [2]. The surface roughness is improved as the etching temperature approaches towards the boiling point of the etchant solution as shown in Figure 4 [2]. In Figure 4 [2], point A indicates highest roughness while point B indicates lowest roughness.

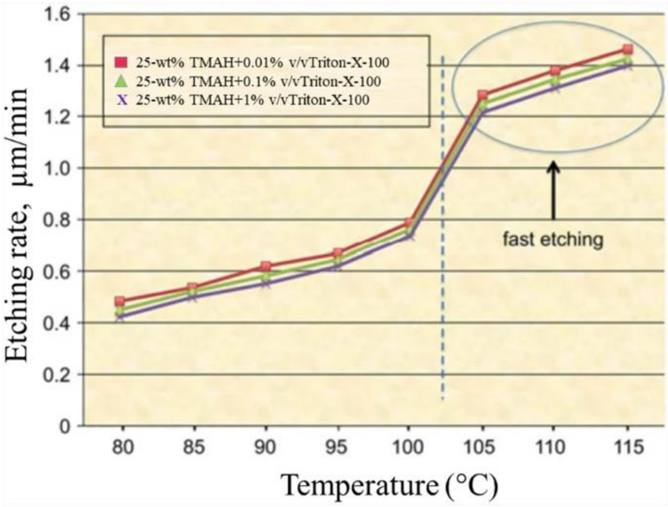

Figure 3:.Etch rate of Si{100} as a function of etching temperature in 25 wt% TMAH with a surfactant Triton-X-100 in a volume fraction of 0.01–1% [2].

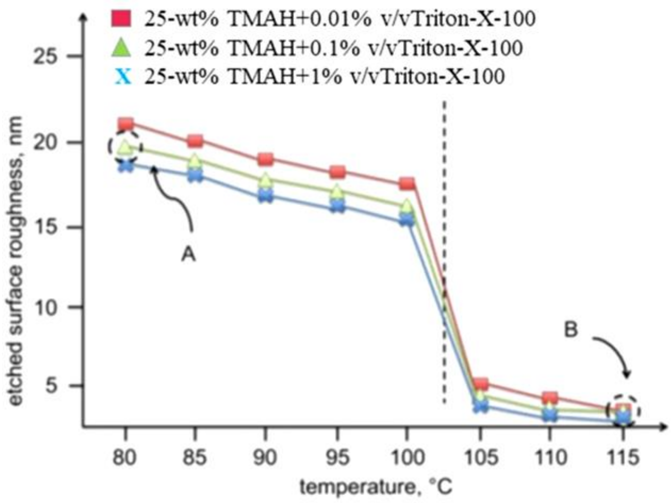

Figure 4: Temperature dependent etched surface roughness of Si {100} in 25 wt% TMAH with Triton-X-100 in a volume fraction from 0.01–1% [2].

These differences make TMAH a more attractive option in many MEMS applications, particularly in terms of safety, precision, and sensor performance.

6. Conclusions

Tetramethylammonium hydroxide (TMAH) has emerged as a key etching solution in the fabrication of MEMS-based sensors, offering a range of advantages that make it an ideal choice for modern sensor technologies. Its high etch rates, excellent anisotropic etching capabilities, compatibility with CMOS processes, low toxicity, and smooth surface finishes contribute to its superiority over traditional etchants like potassium hydroxide (KOH).

The ability of TMAH to create highly precise and well-defined diaphragm structures, combined with its selectivity toward silicon dioxide and silicon nitride as masking materials, enhances its utility in the fabrication of MEMS sensors. As MEMS technology continues to evolve, the use of TMAH will likely play a pivotal role in advancing sensor performance and enabling the next generation of highly efficient, reliable, and compact MEMS devices.

Authors' contributions

The author read and approved the final manuscript.

Conflicts of interest

The author declares no conflict of interest.

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Data availability

No new data were created.

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