MEMS 麦克风技术详解

MEMS Microphone Technology Explained

1. 工作原理：将声波转化为电信号

Working Principle: Converting Sound Waves into Electrical Signals

The core of a MEMS microphone lies in using tiny capacitance changes to sense sound. Its internal structure consists of a diaphragm and a fixed, perforated backplate, forming a miniature capacitor. When sound waves enter, the diaphragm vibrates in response to the sound waves, altering the distance between it and the backplate, thereby causing a change in capacitance that is proportional to the sound pressure.

部结构由一个振膜（Diaphragm）与一个固定的多孔背极板（Backplate）构成微型电容器。当声波传入，振膜随声波振动，改变它与背极板之间的距离，进而导致电容量发生变化，该变化与声压成正比。

To process these minute capacitance changes, an ASIC (Application-Specific Integrated Circuit) chip is integrated inside the microphone. The ASIC is responsible for providing bias voltage, amplifying the signal, and, in digital microphones, performing analog-to-digital conversion, ultimately delivering a high-quality analog or digital signal.

为处理这些微小的电容变化，麦克风内部集成了一颗 ASIC 专用集成电路芯片。ASIC 负责提供偏置电压、放大信号，并在数字麦克风中完成模数转换，最终输出高质量的模拟或数字信号。

MEMS microphones offer both analog and digital output interfaces:

MEMS 麦克风提供模拟和数字两种输出接口：

- Analog Output: Outputs a continuously varying voltage signal. The structure is simple, but it is more susceptible to electromagnetic interference.

- 模拟输出：输出连续变化的电压信号，结构简单，但较易受电磁干扰。

- Digital Output: Common formats include PDM (Pulse Density Modulation) and I^2S (Inter-IC Sound). It can directly connect to digital processors (like DSPs) and offers stronger anti-interference capability.

- 数字输出：常见格式包括 PDM（脉冲密度调制）和 I^2S（集成电路间声频总线），可直接连接数字处理器（如 DSP），抗干扰能力更强。

2. 主要分类：电容式 vs. 压电式

Main Classification: Capacitive vs. Piezoelectric

根据换能方式，MEMS 麦克风主要分为电容式和压电式。

Based on the transduction method, MEMS microphones are primarily divided into capacitive and piezoelectric types.

特性 Feature	电容式 MEMS (Capacitive MEMS) Capacitive MEMS	压电式 MEMS (Piezoelectric MEMS) Piezoelectric MEMS
工作原理 Operating Principle	振膜（可变电极）与固定背极板形成电容器，通过声波振动改变电容来感知声音。 A diaphragm (variable electrode) and a fixed backplate form a capacitor, sensing sound through changes in capacitance caused by acoustic wave vibrations.	振膜上集成压电材料，通过声波振动产生的机械应力直接产生电荷（电压）。 Piezoelectric material is integrated onto the diaphragm, directly generating an electric charge (voltage) from the mechanical stress produced by acoustic wave vibrations.
主要优势 Key Advantages	技术成熟，信噪比（SNR）高，频率响应平坦，一致性好，是当前市场的主流技术。 Mature technology, high signal-to-noise ratio (SNR), flat frequency response, and good consistency; it is the mainstream technology in the current market.	1. 抗污染/坚固耐用：对灰尘、水汽和颗粒物不敏感。 1. Contamination-resistant/Rugged: Insensitive to dust, moisture, and particulate matter. 2. 超高声学过载点 （AOP）：不易失真，可处理高声压级信号。 2. Extremely high acoustic overload point (AOP): Not prone to distortion, capable of handling high sound pressure level signals. 3. 低功耗：无需电荷泵，功耗较低，可用于声音唤醒。 3. Low power consumption: No charge pump required, resulting in lower power usage, suitable for voice wake-up applications.
主要局限 Main Limitations	对灰尘和湿气相对敏感，声学过载点有一定限度。 Relatively sensitive to dust and moisture, with a limited acoustic overload point.	技术仍在持续优化，成本相对较高，频率响应和噪声性能仍有提升空间。 The technology is still being continuously optimized, with relatively high cost and room for improvement in frequency response and noise performance.
典型应用 Typical Applications	广泛适用于各类消费电子产品，如手机、耳机、笔记本电脑等。 Widely used in various consumer electronics, such as smartphones, earphones, and laptops.	专业录音（乐器拾音）、高噪声环境（工业监测）、水下设备、特定通信场景等。 Professional recording (instrument pickup), high-noise environments (industrial monitoring), underwater equipment, specific communication scenarios, etc.

3. 制造工艺：微观结构的精密加工

Manufacturing Process: Precision Machining of Microstructures

MEMS 麦克风的制造体现了半导体技术的精密性，核心流程包括：

The manufacturing of MEMS microphones embodies the precision of semiconductor technology, with the core processes including:

1. 基底准备：通常以硅片为基础材料，有时采用 SOI（绝缘体上硅）衬底以提升性能。

   Substrate Preparation: Typically using silicon wafers as the base material, sometimes employing SOI (Silicon-On-Insulator) substrates to enhance performance.

2. 光刻：通过涂胶、曝光、显影等工序，在硅片上定义出振膜、背极板等微小结构的图案。

   Photolithography: Through processes such as coating, exposure, and development, patterns for tiny structures like the diaphragm and backplate are defined on the silicon wafer.

3. 刻蚀：利用干法或湿法刻蚀技术，有选择性地移除硅材料，形成悬空的三维立体结构，这是制造的核心步骤。

   Etching: Utilizing dry or wet etching techniques to selectively remove silicon material, forming suspended three-dimensional structures, which is a core step in manufacturing.

4. 薄膜沉积：通过 PVD（物理气相沉积）或 CVD（化学气相沉积）等技术，在结构上沉积金属或绝缘材料，以形成电极和功能层。

   Thin-Film Deposition: Using techniques such as PVD (Physical Vapor Deposition) or CVD (Chemical Vapor Deposition) to deposit metal or insulating materials on the structures to form electrodes and functional layers.

5. 振膜制备：通过精确的沉积和刻蚀工艺，形成一个极薄且灵敏的振膜，它决定了麦克风的灵敏度和频率响应。

   Diaphragm Fabrication: Through precise deposition and etching processes, an extremely thin and sensitive diaphragm is created, which determines the microphone's sensitivity and frequency response.

6. 封装：将制造好的 MEMS 芯片和 ASIC 芯片封装在一个带有声学入口的保护外壳中，确保性能稳定可靠。

   Packaging: Encapsulating the fabricated MEMS chip and ASIC chip in a protective housing with an acoustic port to ensure stable and reliable performance.

7. 测试校准：进行严格的电学和声学测试，确保产品达到设计规格。

   Testing and Calibration: Conducting rigorous electrical and acoustic tests to ensure the product meets design specifications.

该领域的技术重点集中在持续提高灵敏度、展宽并平坦化频率响应、降低本底噪声、实现系统级集成、保证长期可靠性以及控制功耗等方面。

The technical focus in this field centers on continuously improving sensitivity, broadening and flattening frequency response, reducing noise floor, achieving system-level integration, ensuring long-term reliability, and controlling power consumption.

4. 关键性能参数解读

Interpretation of Key Performance Parameters

在选择 MEMS 麦克风时，以下核心性能指标值得重点关注：

When selecting a MEMS microphone, the following core performance indicators warrant particular attention:

- 灵敏度 （Sensitivity）：衡量麦克风将声压转换为电信号的效率，通常以负分贝值（dBV 或 dBFS）表示，数值越大，灵敏度越高。

- Sensitivity: Measures the efficiency of the microphone in converting sound pressure into an electrical signal, typically expressed as a negative decibel value (dBV or dBFS); a higher value indicates higher sensitivity.

- 信噪比 （SNR）：指信号与背景噪声的比值（通常为 A 计权，单位 dBA），数值越高，声音越纯净。高端应用通常要求 70dBA 以上。

- Signal-to-Noise Ratio (SNR): Refers to the ratio of the signal to background noise (usually A-weighted, in dBA); a higher value signifies purer sound. High-end applications typically require over 70 dBA.

- 频率响应 （Frequency Response）：指麦克风对不同频率声音的增益。理想情况是平坦的宽带响应，以实现声音的真实还原。

- Frequency Response: Refers to the microphone's gain for sounds of different frequencies. A flat, wideband response is ideal for accurate sound reproduction.

- 声学过载点 （AOP）：指输出信号总谐波失真（THD）达到 10%时的输入声压级（单位 dB SPL），代表可承受的最大不失真音量。一般消费级产品在 120-130 dB SPL，压电式则更高。

- Acoustic Overload Point (AOP): Refers to the input sound pressure level (in dB SPL) at which the total harmonic distortion (THD) of the output signal reaches 10%, representing the maximum distortion-free volume the microphone can handle. Typical consumer products range from 120-130 dB SPL, with piezoelectric types being even higher.

- 功耗 （Power Consumption）：对电池供电设备至关重要。当前高品质 MEMS 麦克风的功耗可控制在较低水平，压电式在特定模式下的功耗更具优势。

- Power Consumption: Critically important for battery-powered devices. The power consumption of current high-quality MEMS microphones can be controlled at low levels, with piezoelectric types offering advantages in specific modes.

- 电源抑制比 （PSRR）：衡量麦克风抑制电源噪声的能力（单位 dB），高 PSRR 意味着在复杂电路环境中可获得更干净的声音信号。

- Power Supply Rejection Ratio (PSRR): Measures the microphone's ability to suppress noise from the power supply (in dB); a high PSRR means cleaner sound signals can be obtained in complex circuit environments.

5. 应用领域与实例

Application Fields and Examples

MEMS 麦克风的应用范围十分广泛：

The application range of MEMS microphones is very broad:

- 消费电子：应用于智能手机、TWS 耳机（语音通话/降噪）、智能音箱（远场语音拾取）等，通常需要高信噪比、低功耗和紧凑的封装。

- Consumer Electronics: Used in smartphones, TWS earbuds (voice calls/noise cancellation), smart speakers (far-field voice pickup), etc., typically requiring high SNR, low power consumption, and compact packaging.

- 汽车电子：应用于车载语音交互、主动降噪等，要求较宽的工作温度范围（如-45°C 至 105°C）和高 AOP（如 130dB SPL）。

- Automotive Electronics: Applied in in-vehicle voice interaction, active noise cancellation, etc., requiring a wide operating temperature range (-45°C to 105°C) and high AOP (e.g., 130 dB SPL).

- 工业与医疗：用于工业设备状态监测（在嘈杂环境中捕捉异常声波）和医疗助听器（要求低功耗、高灵敏度）。

- Industrial and Medical: Used for industrial equipment condition monitoring (capturing abnormal sound waves in noisy environments) and medical hearing aids (requiring low power consumption, high sensitivity).

6. 市场趋势与主要厂商

Market Trends and Major Manufacturers

MEMS 麦克风市场保持增长态势。根据公开的行业分析报告，市场销售额规模持续扩大，数家头部企业引领着行业发展，包括楼氏（Knowles）、歌尔（Goertek）、瑞声科技、意法半导体（STMicroelectronics）、英飞凌（Infineon）和 TDK 等。其中，中国厂商在全球供应体系中占据重要地位。

The MEMS microphone market maintains a growth trajectory. According to publicly available industry analysis reports, the market sales scale continues to expand, with several leading companies driving industry development, including Knowles, Goertek, AAC Technologies, STMicroelectronics, Infineon, and TDK. Among them, Chinese manufacturers hold a significant position in the global supply system.

7. 未来技术趋势

Future Technology Trends

- 更高性能与 AI 集成：追求更高 SNR 以支持人工智能语音交互，同时探索将 AI 降噪算法直接集成到麦克风模组中。

- Higher Performance and AI Integration: Pursuing higher SNR to support artificial intelligence voice interaction, while exploring the direct integration of AI noise reduction algorithms into microphone modules.

- 新型结构与材料：出现了“密封双振膜（SDM）”等新结构，以提升防尘和抗水能力，提升器件可靠性。

- Novel Structures and Materials: New structures such as "Sealed Dual Membrane (SDM)" are emerging to enhance dust and water resistance, improving device reliability.

- 更小尺寸与更低功耗：为适应可穿戴设备、AR/VR 眼镜等，微型化和超低功耗是持续迭代的方向。

- Smaller Size and Lower Power Consumption: To accommodate wearable devices, AR/VR glasses, etc., miniaturization and ultra-low power consumption are directions for continuous iteration.

- 前沿技术探索：新材料（如石墨烯）以及基于光学原理的麦克风技术正处于研究阶段，旨在实现性能的进一步突破。

- Exploration of Cutting-Edge Technologies: Microphone technologies based on new materials (such as graphene) and optical principles are currently in the research stage, aiming for further breakthroughs in performance.

本文内容基于行业公开资料整理，仅供参考。

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