驻极体电容麦克风技术详解

Detailed Explanation of Electret Condenser Microphone Technology

一、工作原理 Working Principle

1.1 核心工作机制 Core Operating Mechanism

驻极体电容麦克风（ECM）的基本原理是可变电容的充放电效应。当声波作用于振膜时，振膜与背极板之间的距离发生周期性变化，根据平行板电容器公式 $C = \varepsilon A / d$（其中 *d* 为板间距），电容值相应改变。由于驻极体材料上的电荷量 *Q* 在短期内几乎保持不变（*$Q = C \cdot V$*），电容的变化最终引起电压的变化：$\Delta V = Q / \Delta C$。这一微弱的电压变化随后由内置的 JFET（结型场效应晶体管） 进行放大和缓冲输出。

The basic principle of an electret condenser microphone (ECM) is the charge-discharge effect of a variable capacitor. When sound waves act on the diaphragm, the distance between the diaphragm and the backplate changes periodically. According to the parallel-plate capacitor formula $C = \varepsilon A / d$ (where *d* is the plate spacing), the capacitance value changes accordingly. Since the charge amount *Q* on the electret material remains almost constant in the short term (*$Q = C \cdot V$*), the change in capacitance ultimately causes a voltage change: $\Delta V = Q / \Delta C$. This weak voltage change is then amplified and buffered for output by the built-in JFET (Junction Field-Effect Transistor).

1.2 等效电路模型 Equivalent Circuit Model

- 信号源：ECM 可等效为一个高输出阻抗的电容性电压源。

- Signal Source: An ECM can be equivalent to a capacitive voltage source with high output impedance.

- 缓冲级：换能部分本征输出阻抗极高，需通过一个单位增益缓冲器（即 JFET）将阻抗降至通常在 2.2 kΩ 以下，以确保信号有效传输至下一级电路。

- Buffer Stage: The intrinsic output impedance of the transducer part is extremely high and must be reduced to typically below 2.2 kΩ by a unity-gain buffer (i.e., the JFET) to ensure effective signal transmission to the next stage circuit.

- 输出级：JFET 的输出端外接隔直电容，滤除直流偏置成分，输出纯净的交流音频信号。

- Output Stage: The JFET's output terminal is externally connected to a DC-blocking capacitor, filtering out the DC bias component and outputting a pure AC audio signal.

二、内部构造与类型 Internal Structure and Types

2.1 内部组成 Internal Components

ECM 的典型结构（由声音入口向内）包括：

The typical structure of an ECM (from the sound inlet inward) includes:

- 不织布：防尘、颗粒防护。
- Non-woven Fabric: Dust and particle protection.

- 外壳：金属材质，提供保护与电磁屏蔽。

- Housing: Metal material, providing protection and electromagnetic shielding.

- 极环：用于固定振膜。

- Pole Ring: Used to secure the diaphragm.

- 振膜：极薄的聚酯膜片，单面镀金属，为声音接收和电容变化的核心。

- Diaphragm: Extremely thin polyester film, metal-plated on one side, serving as the core for sound reception and capacitance change.

- 隔片（Spacer）：精密控制振膜与背板间的气隙间距。

- Spacer: Precisely controls the air gap distance between the diaphragm and the backplate.

- 背板（Backplate）：带声学阻尼小孔的固定金属电极。

- Backplate: A fixed metal electrode with acoustic damping holes.

- 底座：容纳背板和内部电路，提供对外接口。

- Base: Houses the backplate and internal circuitry, providing the external interface.

2.2 驻极体类型 Electret Types

表 1：麦克风类型对电容与电荷的影响

Table 1: Impact of Microphone Type on Capacitance and Charge

影响参数 Affecting Parameters	前驻极体（振膜式） Front Electret (Diaphragm Type)	后驻极体（背极式） Back Electret (Backplate Type)
初始电容 Initial Capacitance	较低（振膜轻） Lower (light diaphragm)	较高（背极板贡献） Higher (contribution from backplate)
电荷稳定性 Charge Stability	一般（受振膜应力影响） Average (affected by diaphragm stress)	较高（结构更稳定） Higher (more stable structure)
声学性能 Acoustic Performance	高频延展性更好 Better high-frequency extension	一致性、信噪比更高 Higher consistency and signal-to-noise ratio

2. 前驻极体（Foil/Front Electret）：常见低成本方案。驻极体材料直接作为振动膜片，同时担负接收声波和提供极化电荷的功能。

1. Foil/Front Electret: A common low-cost solution. The electret material itself serves as the diaphragm, simultaneously receiving sound waves and providing polarization charge.

3. 后驻极体（Back Electret）：专业级常用方案。驻极体材料固定于背极板，振膜仅负责声波振动。此结构使驻极体电荷更稳定，一致性和信噪比更优。

2. Back Electret: A scheme commonly used in professional-grade microphones. The electret material is fixed to the backplate, while the diaphragm is only responsible for acoustic vibration. This structure provides more stable electret charge, better consistency, and superior signal-to-noise ratio.

三、关键性能参数 Key Performance Parameters

- 频率响应：标准消费级 ECM 通常为 20 Hz ~ 20 kHz，覆盖人耳听觉范围。

- Frequency Response: Standard consumer-grade ECMs typically range from 20 Hz to 20 kHz, covering the human auditory range.

- 灵敏度：衡量声-电转换效率，常用 1 Pa 声压下的输出电压表示。消费类典型值为 -40 dB（约

10 mV/Pa） 至 -36 dBV/Pa，分贝值越接近 0 灵敏度越高。

- Sensitivity: Measures the acoustic-to-electrical conversion efficiency, often expressed as output voltage under 1 Pa sound pressure. Typical values for consumer products range from -40 dB (approx. 10 mV/Pa) to -36 dBV/Pa; the closer the decibel value is to 0, the higher the sensitivity.

- 信噪比（SNR）：典型值在 55 dBA 至 >70 dBA。SNR 高于 70 dB 时，可闻的“嘶嘶”声显著降低。

- Signal-to-Noise Ratio (SNR): Typical values range from 55 dBA to >70 dBA. When the SNR is higher than 70 dB, audible "hiss" is significantly reduced.

- 动态范围：从本底噪声到最大不失真声压级（SPL）的范围。高质量 ECM 典型值约 111~124 dB，最大声压级可达 144 dB SPL。

- Dynamic Range: The range from the self-noise floor to the maximum undistorted Sound Pressure Level (SPL). Typical values for high-quality ECMs are about 111~124 dB, with a maximum SPL capable of reaching 144 dB SPL.

- 输出阻抗：消费类低阻抗典型值约 2.2 kΩ，专业级平衡输出可低至 100~200 Ω。

- Output Impedance: Typical low-impedance consumer values are about 2.2 kΩ; professional balanced outputs can be as low as 100~200 Ω.

- 指向性：包括全指向（Omni）、心形指向（Cardioid）、超心形指向（Supercardioid）及 8 字形（Figure-8）等。

- Directivity: Includes omnidirectional, cardioid, supercardioid, and figure-8 patterns, among others.

- 工作电压与电流：消费类 ECM 典型供电电压 1.5~10 V，电流约 500 μA （0.5 mA）。

- Operating Voltage and Current: Typical supply voltage for consumer ECMs is 1.5~10 V, with a current of approximately 500 μA (0.5 mA).

四、内部电路设计 Internal Circuit Design

4.1 基础偏置电路 Basic Bias Circuit

ECM 内部通常集成共源极或源极跟随器配置的 JFET 进行阻抗变换。核心电路为“电阻偏置 + 隔直电容”：

ECMs typically integrate a JFET in a common-source or source-follower configuration for impedance conversion. The core circuit is a "resistor bias + DC blocking capacitor":

- 偏置电阻 Rb（通常 1~2.2 kΩ）：连接电源正极与 ECM 输出端，为 JFET 提供直流工作点。阻值较大时可获得更高增益，但会限制最大不失真声压级。

- Bias Resistor Rb (usually 1~2.2 kΩ): Connects the positive power supply terminal to the ECM output, providing a DC operating point for the JFET. Higher resistance values can yield higher gain but limit the maximum undistorted SPL.

- 隔直电容 Cb：从 Rb 与输出连接点引出，隔离电源直流分量，输出纯净交流信号。

- DC Blocking Capacitor Cb: Connected from the junction of Rb and the output, it isolates the DC component of the power supply and outputs a pure AC signal.

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`VCC
 |
 |     Rb （偏置电阻，如 2.2kΩ）
 |     Rb (Bias Resistor, e.g., 2.2kΩ)
 |
麦克风输出引脚 ————┤ ├————> 音频输出 （至 ADC 或放大器）
Mic Output Pin ————┤ ├————> Audio Output (to ADC or Amplifier)
 |          Cb （隔直电容）
 |          Cb (DC Blocking Capacitor)
 |
GND
```

4.2 进阶电路：射频滤波与平衡输出 Advanced Circuits: RF Filtering and Balanced Output

- RF 防护：现代 ECM 可集成滤波电容，配合贴片铁氧体磁珠构成低通电源滤波器，有效抑制移动电话、Wi-Fi 等射频干扰。

- RF Protection: Modern ECMs can integrate filter capacitors, combined with chip ferrite beads, to form low-pass power supply filters, effectively suppressing RF interference from mobile phones, Wi-Fi, etc.

- 平衡传输：专业音频领域，ECM 可通过内置或外接变压器，将非平衡单端输出转换为平衡差分信号（如 XLR 接口），具备强共模抑制能力，可支持数百米无源长线传输。

- Balanced Transmission: In professional audio, ECMs can convert the unbalanced single-ended output into a balanced differential signal (e.g., XLR interface) via built-in or external transformers, providing strong common-mode rejection and supporting passive long cable runs of hundreds of meters.

4.3 集成前端：放大与模数转换 Integrated Front-End: Amplification and Analog-to-Digital Conversion

- 集成放大器：ECM 原始信号仅数毫伏，可由 CMOS 集成运放提供 24 dB 或更高固定增益，放大至线路电平，直接驱动模数转换器（ADC）。

- Integrated Amplifier: The raw ECM signal is only a few millivolts. A CMOS integrated operational amplifier can provide 24 dB or higher fixed gain, amplifying it to line level to directly drive an ADC.

- 全集成数字 ECM：以包含 ΣΔ 模数转换器和数字接口的 ASIC 替代 JFET，可在同一金属壳内直接输出数字 PDM 或 I^2S 格式信号，本征抗噪能力强。

- Fully Integrated Digital ECM: Replaces the JFET with an ASIC containing a ΣΔ analog-to-digital converter and a digital interface, capable of directly outputting digital PDM or I^2S format signals within the same metal housing, with intrinsically strong noise immunity.

4.4 经典参考电路 Classic Reference Circuit

以下为一例包含射频防护和共模抑制的分立元件 ECM 放大电路。

Below is an example of a discrete-component ECM amplifier circuit incorporating RF protection and common-mode rejection.

>https://img.elecfans.com/article/UploadPic/2009-11/2009112217387075.bmp

电路节点详解：

Circuit Node Details:

1. 偏置电阻（R1）：提供 JFET 源极跟随器工作点，应选用低热噪声金属膜电阻或绕线电阻。

1. Bias Resistor (R1): Provides the operating point for the JFET source follower. Low thermal noise metal film or wire-wound resistors should be selected.

2. 射频旁路电容（C1）：置于电源与地之间，滤除电源纹波和射频干扰。

2. RF Bypass Capacitor (C1): Placed between the power supply and ground to filter supply ripple and RF interference.

3. 运放差分放大器：将单端输入信号转换为不受地环路噪声影响的平衡差分信号，大幅提升抗干扰能力，适合长距离传输。

3. Op-Amp Differential Amplifier: Converts the single-ended input into a balanced differential signal unaffected by ground loop noise, greatly enhancing interference immunity and suitability for long-distance transmission.

五、应用领域 Application Fields

- 消费电子：手机、TWS 真无线耳机、录音笔、有/无线耳机、笔记本电脑集成麦克风阵列等。

- Consumer Electronics: Mobile phones, TWS earbuds, voice recorders, wired/wireless headphones, integrated microphone arrays in laptops, etc.

- 专业音频：枪式采访麦克风、鹅颈会议麦克风、乐器拾音、广播级头戴耳麦（典型产品如 Audio-Technica AT2020、Sony ECM-678 系列）。

- Professional Audio: Shotgun interview microphones, gooseneck conference microphones, instrument pickups, broadcast-grade headsets (typical products include the Audio-Technica AT2020, Sony ECM-678 series).

- 工业与医疗：声学振动传感器、心音监测、工业噪声监测、语音识别模组等。

- Industrial and Medical: Acoustic vibration sensors, heart sound monitoring, industrial noise monitoring, voice recognition modules, etc.

- 助听器：ECM 的经典核心应用，全球超 90%助听器采用超微型 ECM 咪头，得益于其模拟高增益与可靠声反馈特性。

- Hearing Aids: A classic core ECM application; over 90% of global hearing aids use subminiature ECM capsules, benefiting from their analog high-gain and reliable acoustic feedback characteristics.

六、发展趋势与挑战 Development Trends and Challenges

尽管 MEMS 麦克风在便携式消费电子领域增长迅猛，ECM 技术本身仍持续深化其性价比优势，总体趋势包括：

Although MEMS microphones are rapidly growing in the portable consumer electronics sector, ECM technology continues to deepen its cost-performance advantages. General trends include:

- 材料升级：采用纳米纤维、石墨烯等新型驻极体材料，提升电荷密度和高温稳定性（可达 85° C 或更高）。

- Material Upgrades: Adoption of novel electret materials such as nanofibers and graphene to enhance charge density and high-temperature stability (capable of 85° C or higher).

- 工艺融合：将 MEMS 微加工工艺与传统 ECM 封装结合，制造更精密、一体化的产品，提升灵敏度和一致性。

- Process Integration: Combining MEMS micromachining processes with traditional ECM packaging to create more precise, integrated products, improving sensitivity and consistency.

- 微型化：开发直径不足 2.5 mm 的超微型产品，满足无线耳机、医疗内窥镜等设备的严苛空间要求。

- Miniaturization: Development of subminiature products less than 2.5 mm in diameter to meet the stringent space requirements of devices like wireless earbuds and medical endoscopes.

- 智能化：与模拟前端（AFE）深度融合，ECM 输出的模拟信号可直接经高精度 ΣΔ ADC 转换并集成 DSP 处理，实现本地关键词唤醒、环境降噪等功能。

- Intelligence: Deep integration with Analog Front-Ends (AFEs); the ECM's analog output signal can be directly converted by high-precision ΣΔ ADCs and integrated with DSP processing to enable local keyword wake-up, environmental noise reduction, and other functions.

- 绿色制造：开发无铅环保极化工艺，优化免焊接装配工艺。

- Green Manufacturing: Development of lead-free, environmentally friendly polarization processes, optimizing solderless assembly processes.

凭借不可替代的中频人声亲和力和极低物料成本，ECM 在语音会议、专业乐器、听力辅助及广域监控等高端模拟领域仍占据稳固地位。

With its irreplaceable affinity for mid-frequency vocals and extremely low material cost, ECMs still hold a solid position in high-end analog domains such as voice conferencing, professional instruments, hearing assistance, and wide-area monitoring.

七、环境耐久性保障设计 Environmental Durability Assurance Design

ECM 对抗极端温度循环及高湿环境的核心在于振膜工艺、涂层及密封方面的保障设计：

The core of ECM durability against extreme temperature cycling and high-humidity environments lies in the diaphragm manufacturing process, coatings, and sealing assurance designs:

- 聚酰亚胺 (PI) 或 PPS 振膜：保证在 -40° C 至 +85° C 之间保持相近的张力与灵敏度，可耐受工业级温循测试。

- Polyimide (PI) or PPS Diaphragms: Ensure similar tension and sensitivity are maintained between -40° C and +85° C, capable of withstanding industrial-grade thermal cycle tests.

- 氟碳纳米涂层：在振膜表面形成惰性防湿层，配合聚全氟乙丙烯 (FEP) 驻极体，保障电荷量长久稳定。

- Fluorocarbon Nanocoating: Forms an inert moisture-proof layer on the diaphragm surface, cooperating with fluorinated ethylene propylene (FEP) electrets to guarantee long-term charge stability.

- 物理防尘与疏水透气膜 （ePTFE）：在设备外壳集成膨体聚四氟乙烯薄膜，阻止液体、汗渍、高湿气渗透，防止极板间结露短路。

- Physical Dust and Hydrophobic Breathable Membrane (ePTFE): Integrating expanded polytetrafluoroethylene film in the device housing prevents the ingress of liquids, sweat, and high humidity, preventing condensation-induced short circuits between plates.