Electroacoustics of MEMS microphones

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Microphones

- More than 2 billion produced annually and growing. 650 million just for cell phones
- Most microphones are based on inexpensive commodity electret-condenser design
- Desire for better performance in mobile speech communications and speech recognition is driving demand for new microphone solutions
- Multiple microphones as well as other sensors combined with associated signal processing is gaining interest

May 31 2004 EE Times “Prediction”

MEMS look to optics, cell phones

By Marlene Bourne

The latter part of 2004 is shaping up to be very good for microelectromechanical systems (MEMS) suppliers. Despite lingering uncertainty on the foundry side regarding consolidation, venture capitalists are investing again, potential customers continue to raise their level of interest and several applications that MEMS suppliers have long been pursuing are now finally coming to fruition. With improved market conditions, the telecommunications market is looking better than ever before, and offers two key end uses to watch during the next few quarters: optical networking and cell phones.

Optical networking certainly doesn't conjure the same level of excitement that it did several years ago, but the fact remains that there is indeed opportunity in this market niche. While there are far fewer MEMS startups pursuing these opportunities than there were several years ago, and the solutions being offered are much different from what first emerged, there are still approximately two dozen companies focused on this space. What is most encouraging is that nearly two-thirds are now generating revenues, with much of the sales activity beginning in earnest in the last quarter of 2003.

That's in line with indications of increased customer interest in early 2003. The recent upswing in revenues has been supported by more customer announcements in early 2004, suggesting that MEMS suppliers in this sector are finally on track for success. To what extent depends on expectations, which should be somewhat tempered, as the giddy days of 2000 and 2001 aren't likely to re-emerge anytime soon. There is no question, however, that a number of companies will indeed find success here.

As an end-use application, supplier as well as customer interest in MEMS and cell phones has been percolating for quite some time. While some MEMS devices for cell phones are the result of offering a solution to a real need (in the form of smaller, improved solutions over existing technologies), other MEMS devices have had to create the demand by pushing use of the technology in some areas. This can be not only incredibly difficult, but also typically does not succeed. The good news is, for some MEMS devices, it appears that the technology push has been successful.

> **The device most likely to succeed is the first MEMS microphone to be put into a cell phone.**

The best example of market pull to date is Agilent Technologies Inc.'s FBAR duplexer and filter. The duplexers alone can be found in nearly five dozen mobile-phone platforms, and have already captured more than 70 percent of the code-division multiple-access phone segment. In late January, the company introduced second-generation duplexers and full-band transmit filters, both of which are 66 percent smaller than their first-generation counterparts.

The MEMS device most likely to follow in Agilent's (Palo Alto, Calif.) footsteps is the microphone. Here, integration resulted from more of a technology push than market pull: The electret condenser microphone, the entrenched technology, is small, inexpensive an sufficiently useful. Nevertheless, the demonstrate improvements of MEMS microphones, at the sam cost, should no doubt create an eventual strong market pull. The first MEMS microphone to be integrate into a cell phone, from Knowles Acoustics, a divisio of Knowles Electronics LLC, was slated to hit the market in May 2003, in the N1 phone from Neonode. Th much-anticipated smart phone has suffered from continuous delays, however, and the company has pushe the launch back to later this year.

Even so, both Knowles an Akustica Inc. (Pittsburgh) ar well-situated to fulfill the expected demand from the value proposition that MEMS microphone offer. As a result, increased momentum in the cell phone marke is likely to begin this fall.

The use of accelerometers i cell phones to scroll throug screens is clearly all technology push. One doesn't nee to tilt the phone to scroll through screens, as oppose to pushing buttons, which have always worked perfectly well. Long discussed by many suppliers of MEM accelerometers, no traction was achieved until recently. The company that has opened the door is MyOrig (Finland), whose MyDevice smart phone will b launched in Europe this summer. It is the first ce phone to use MEMS accelerometers for this purpose and by many accounts, will by no means be the last.

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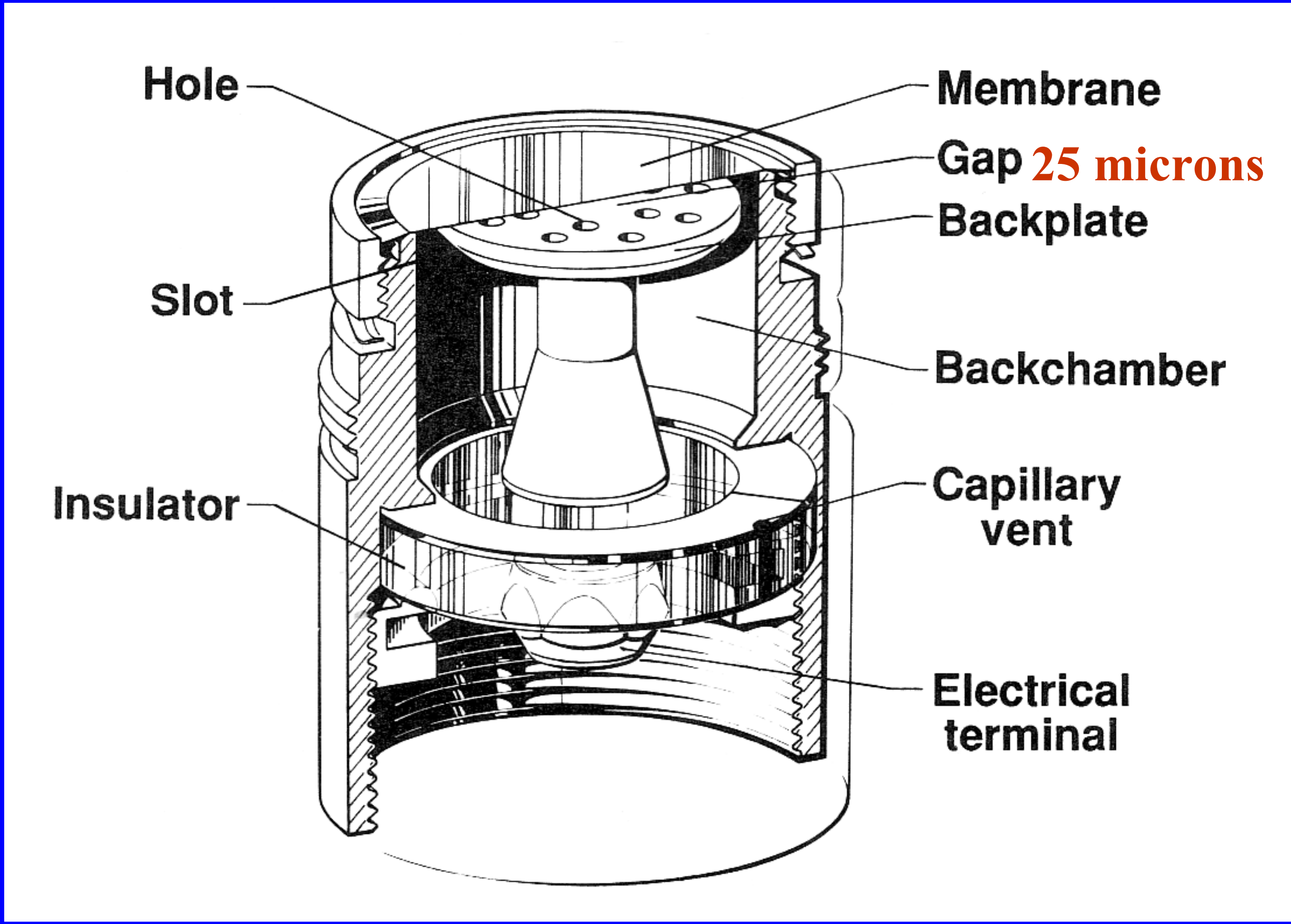
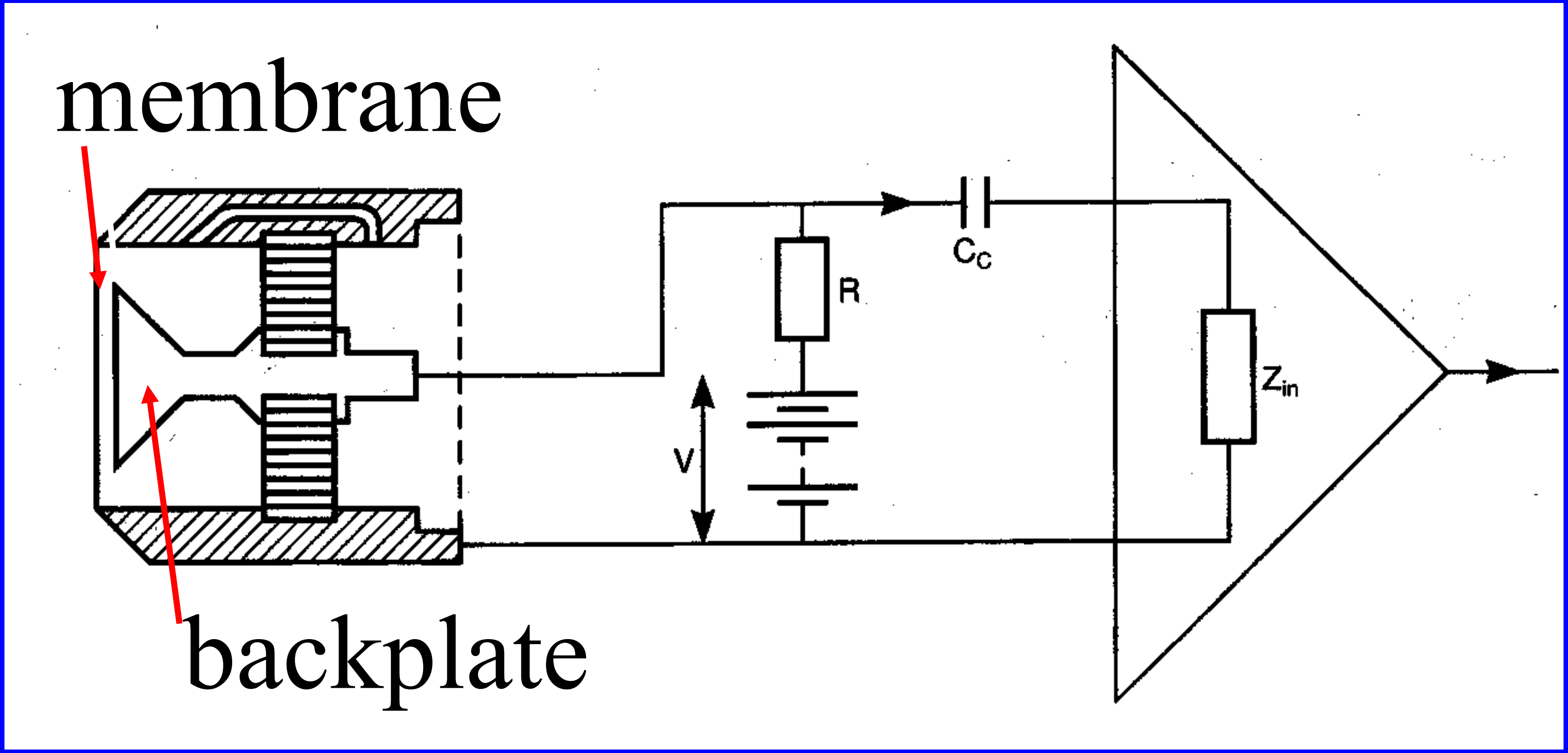
Condenser (electret) Microphone



Condenser Microphone

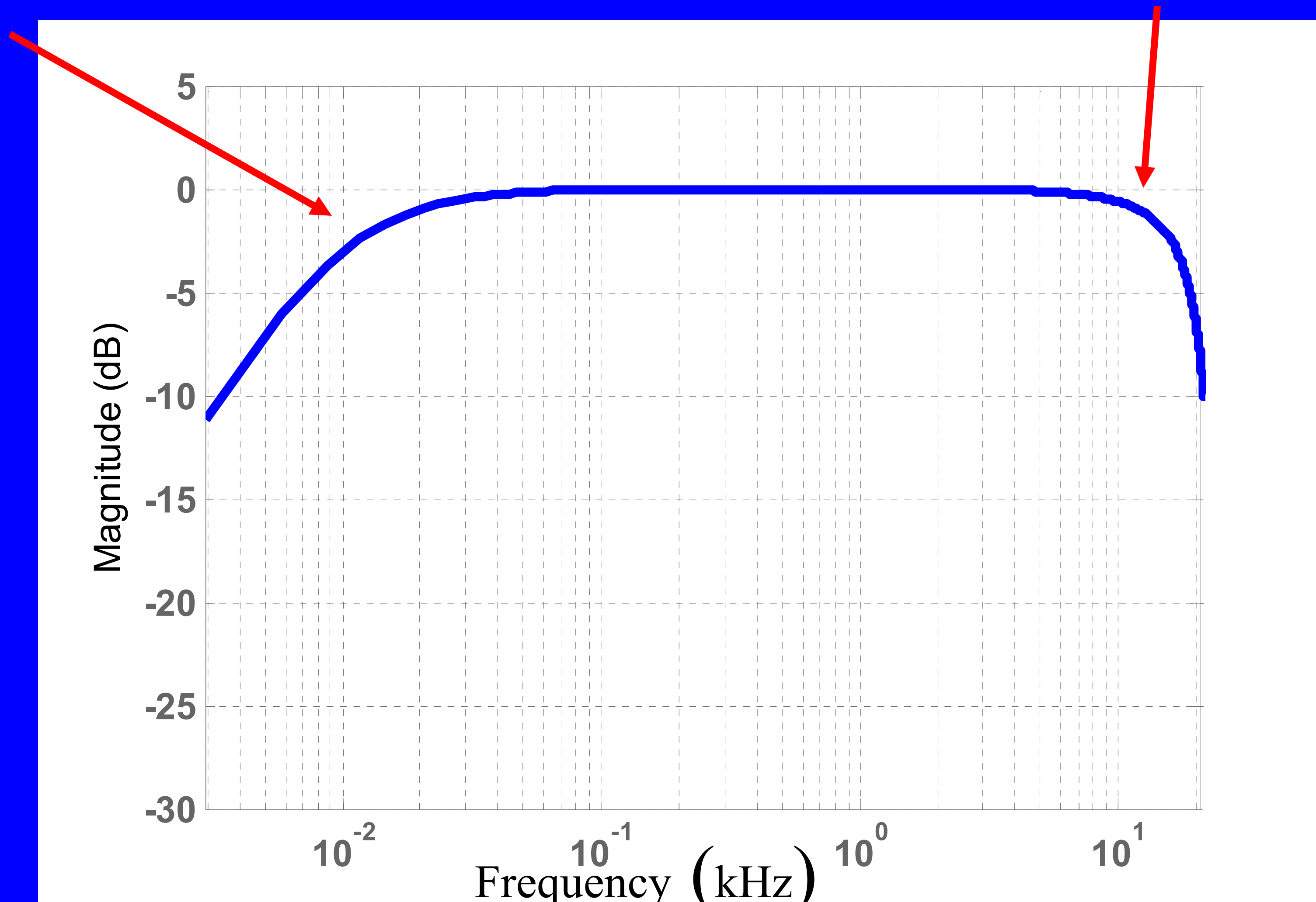


$$Q = CV, \quad C = \frac{\epsilon A}{d}, \quad \Delta V = \frac{Q}{\Delta C} = \frac{Q \Delta d}{\epsilon A}$$

Condenser Microphone

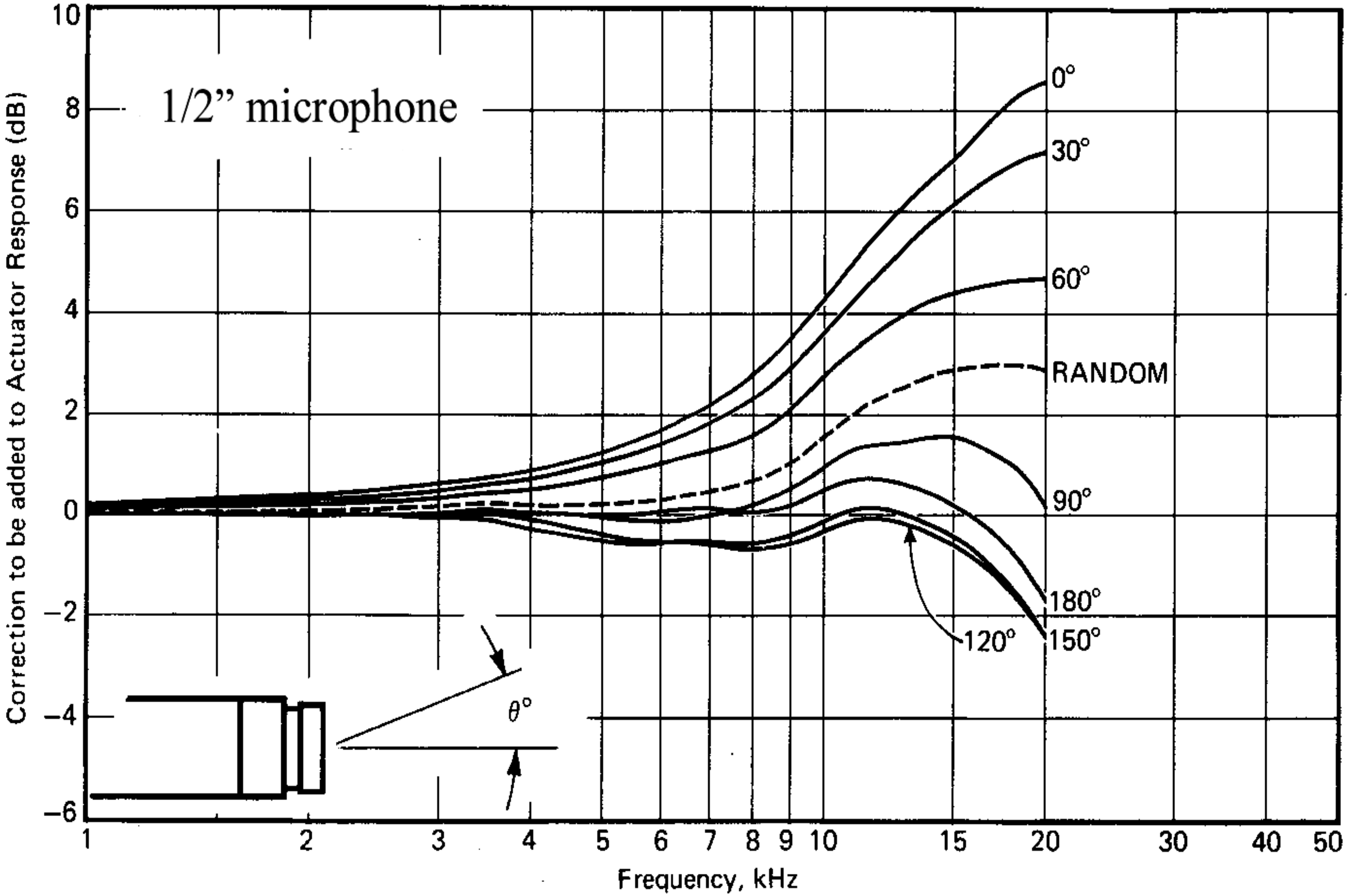
- Can be modeled as a simple single DOF spring-mass system
- Stiffness control region (flat response below resonance)
- Responds to the scalar acoustic pressure (same as ear)
- Linear over human hearing dynamic range
- Requires a polarization bias charge (internal or external)
- Electret-Condenser most produced microphone
- Low mass diaphragm results in less vibration sensitivity
- Self-noise typically less than 30 dBA
- Simple construction and can be very low cost <$0.10

Frequency Response



Why MEMS microphones ?

- Small in size and weight
  - Good for hearing aids and cell phones
  - minimizes disturbance to the sound field
  - low mass diaphragm results in low vibration sensitivity



1/2" microphone
Correction to be added to Actuator Response (dB)
10
8
6
4
2
0
−2
−4
−6
0°
30°
60°
RANDOM
90°
180°
120°
150°
θ°
1
2
3
4
5
6
7
8
9
10
15
20
30
40
50
Frequency, kHz

Why MEMS microphones ? (cont)

- Same manufacturing process as IC Fab
  - low cost (price drops as fab cost drops)
  - standard IC pick-and-place packaging
  - leverage advances in IC fabrication
  - inexpensive and rapid device modification
  - finer specification tolerance / reproducibility
- Direct integration with A/D and DSP
- Ease of combination with multiple sensors

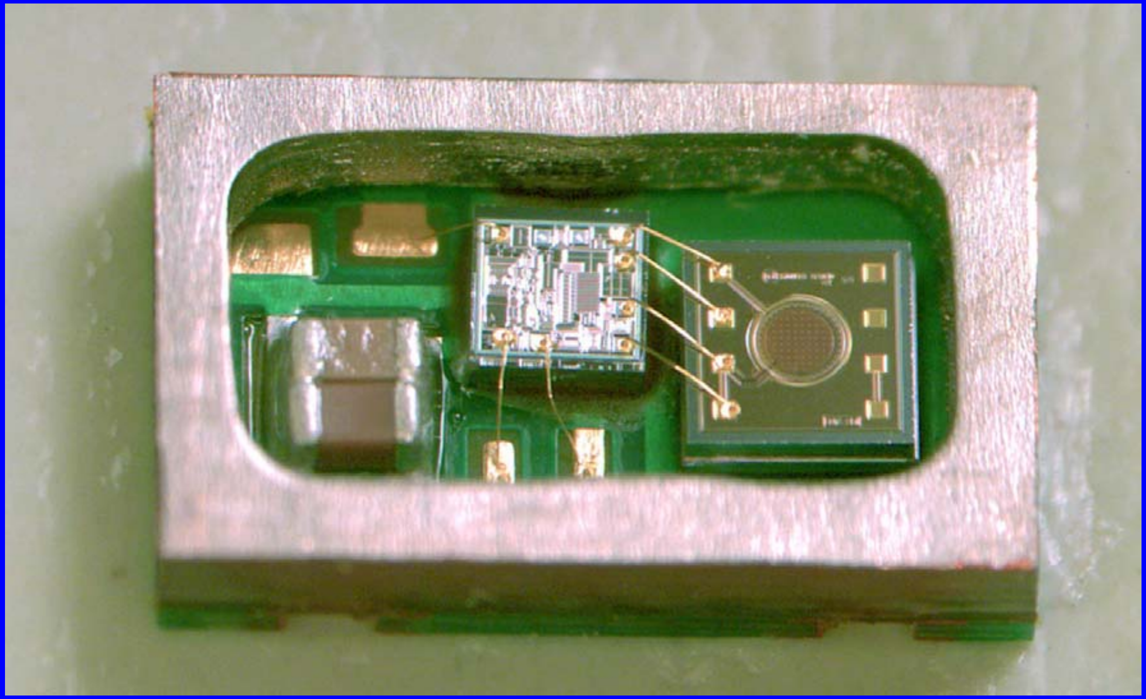
Current drivers for MEMS microphones

- Hearing aids
  - smaller size and weight
  - multiple microphones on a single chip (directionality)
  - cost, reliability, and potential for simplified assembly
- Cellular phones, PC's, and PDA's
  - integration with automatic manufacturing processes
  - integration of microphone with A/D and DSP
  - improved acoustic performance for speech and ASR
  - cost, reliability, specification tolerance, and reproducibility

MEMS Microphone processing techniques

- Bulk micromachining
  - selective removal of wafer substrate
  - compatible with current IC processes
  - currently limited to pressure sensing only
- Surface micromachining
  - deposition and removal of thin structural layers
  - enables devices that are 3D (out-of-plane)
  - flexibility to build more complex array structures

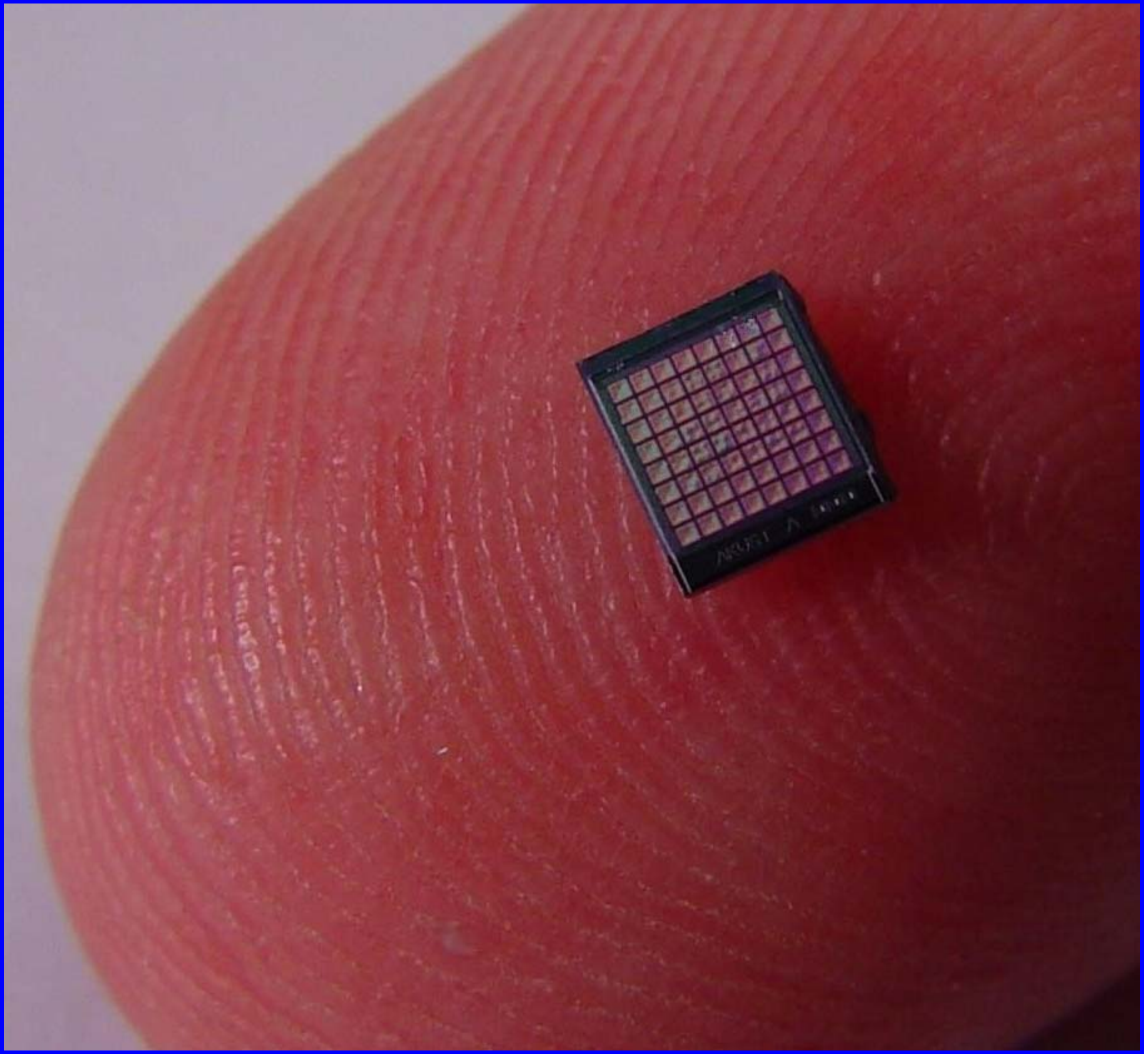
Knowles SiSonic
surface and bulk micromachining



source: Knowles

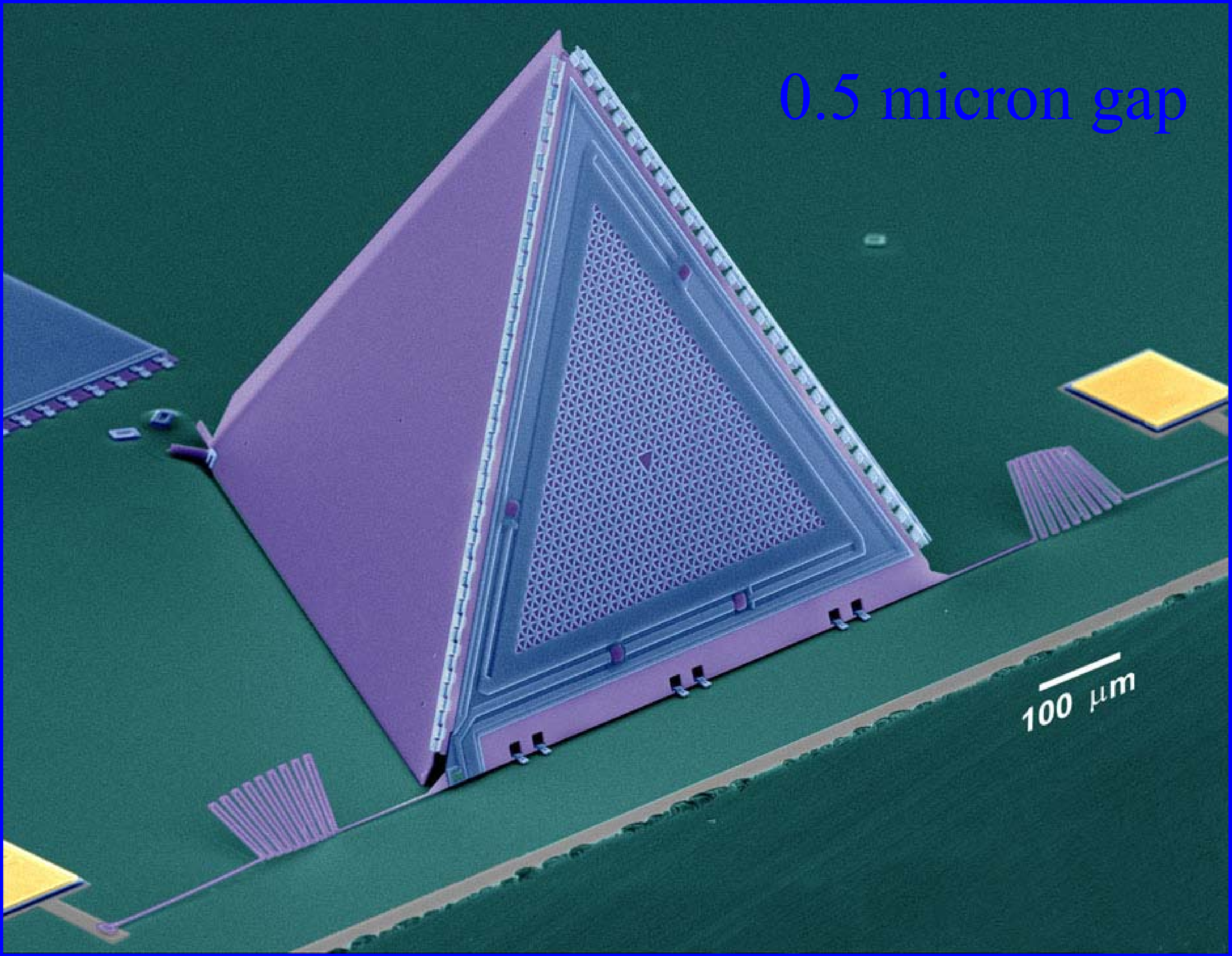
diaphragm: 0.5mm x 1µm   gap: 4 µm

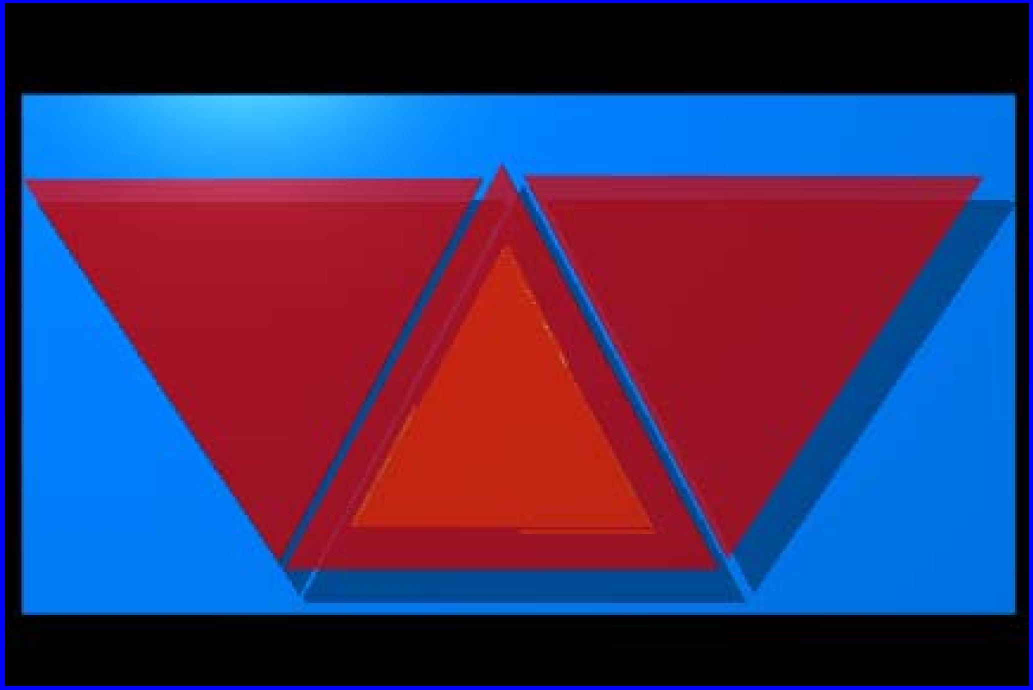
Akustica – Bulk Machining



1 mm^2 , teflon diaphragms PASI 2004 source:Akustica

Bell Labs “Tent” all-surface machined microphone





Current issues with MEMS microphones

- Signal-to-noise ratio is usually too low (>35 dBA)
- MEMs processes not always compatible with standard CMOS fabrication (requires two chips)
- Environmental robustness and stability
- Higher unit cost versus commodity electret
- Aside from pick-and-place and potential higher temperature operation; no added functionality and reduced noise performance over standard electret

Where does the noise come from?

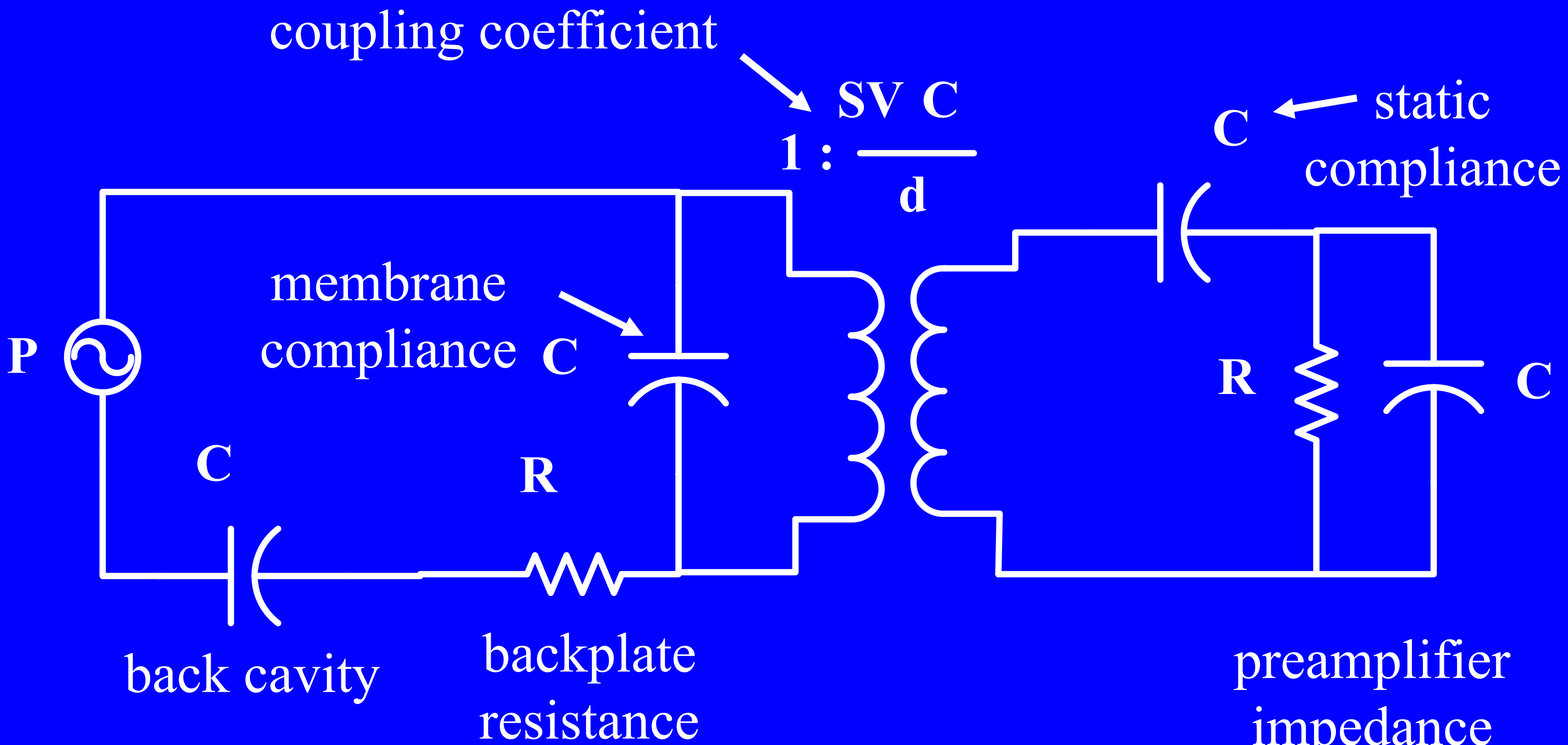
From Nyquist's relation, noise equivalent acoustic pressure is:

$$p_n = \sqrt{4k_B T R_{AS}} \quad [N/\sqrt{Hz}]$$

where the acoustic resistance, R_{AS}

$$R_{AS} = \frac{R_M}{S^2}$$

Low frequency equivalent circuit (impedance analogy)



acoustic domain

electrical domain

Diaphragm / Back-Volume Compliance

The membrane mechanical compliance is:

$$C_M = \frac{S^2}{8\pi T} \text{ , T = membrane tension}$$

The back cavity mechanical compliance is:

$$C_{M2} = \frac{C_{A2}}{S^2} = \frac{V}{\rho_o c^2 S^2}$$

Typical design goal: $C_{M2} >> C_M$

Acoustic resistance of viscous squeeze-film flow between parallel circular plates

For parallel disks of area S,

$$R_{AS} = \frac{3\mu}{2\pi d^3} \quad [N \cdot s/m]$$

gap spacing is d and the fluid viscosity is μ

Acoustic resistance of viscous squeeze-film damping with one perforated disk

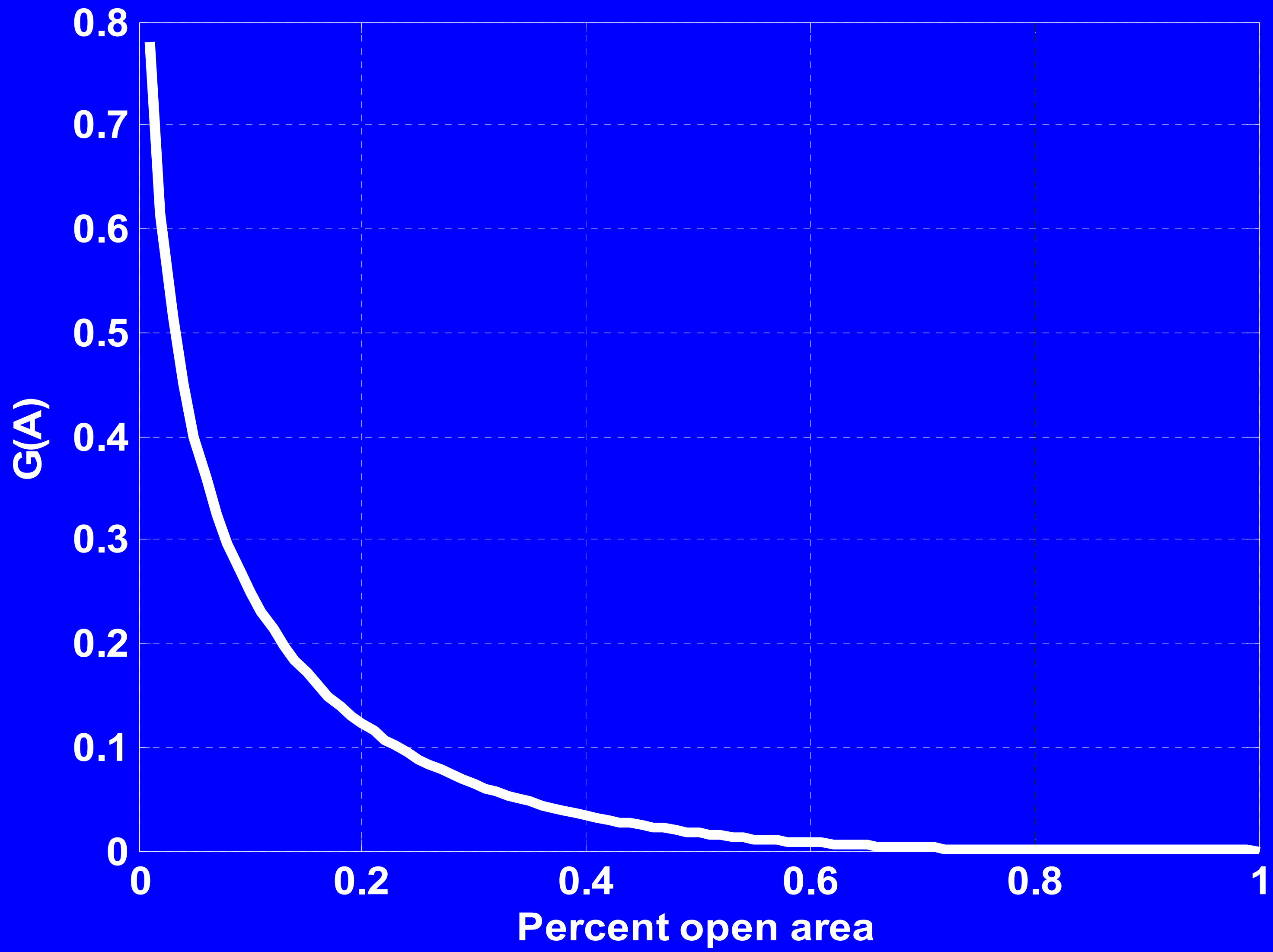
For parallel perforated disks of area S,

$$R_{AS} \approx \frac{12\mu G(A)}{N\pi d^3}$$

N is the number of holes, A is fraction of open area

$$G(A) = \left[\frac{A}{2} - \frac{A^2}{8} - \frac{lnA}{4} - \frac{3}{8}\right]$$

G(A) function



Acoustic resistance due to viscous fluid flow in the microphone gap

For parallel and perforated backplates

$$p_n^2 \propto R_{AS} \propto d^{-3}$$

$$p_s^2 \propto 1/d^2$$

where d is the microphone gap

$$SNR \propto d$$

Radiation Resistance

The real part of the radiation impedance is another noise source ($ka < 1$).

$$R_{AR} \approx \rho S (ka)^2 / 4$$

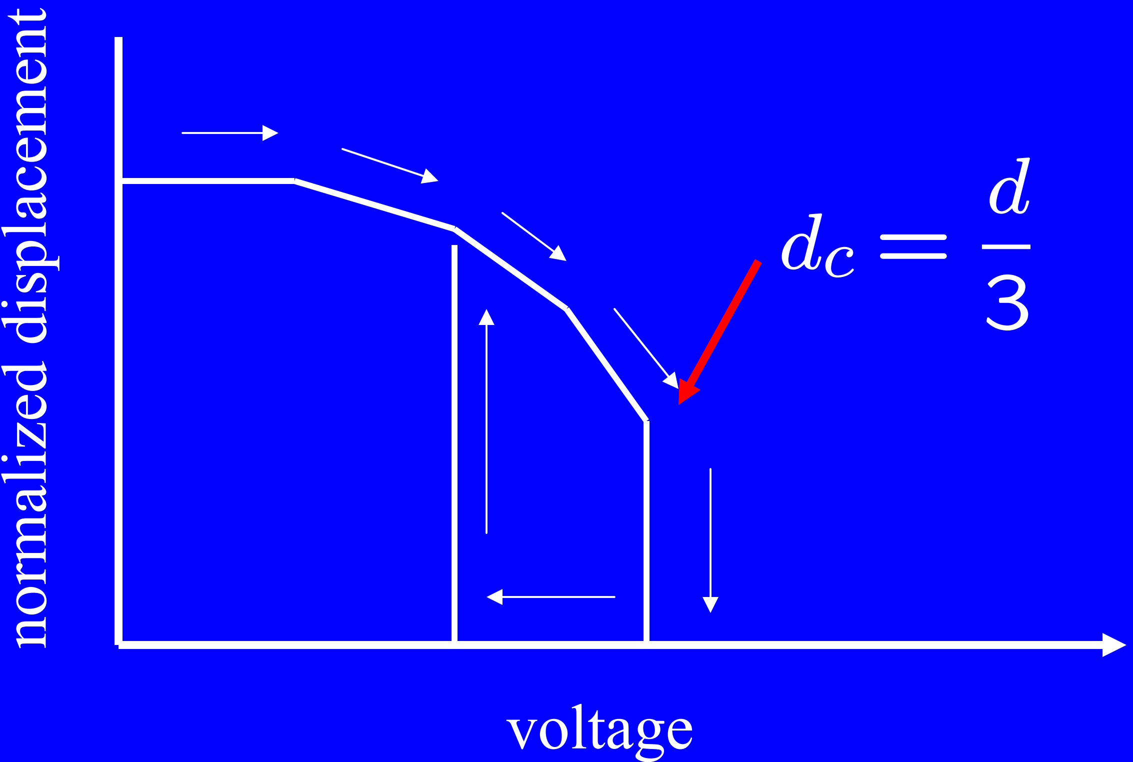
where k is the wavenumber (ω/c), ρ and c are the density and sound speed.

For small $ka < 1$ this term is much less than the viscous fluid damping term R_{AS}

Ways to reduce MEMS noise

Coupling coefficient $$\phi = \frac{S C_M V_o}{d}$$

- Increase the bias voltage

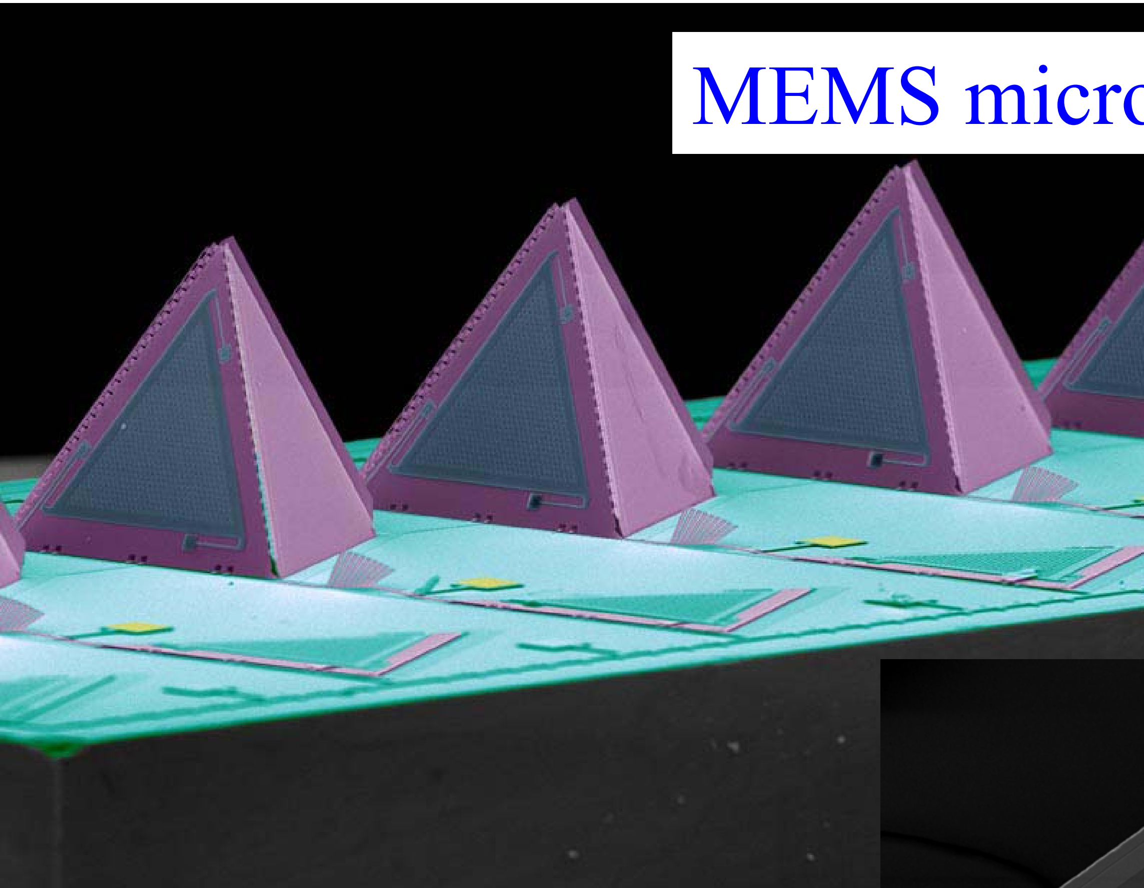


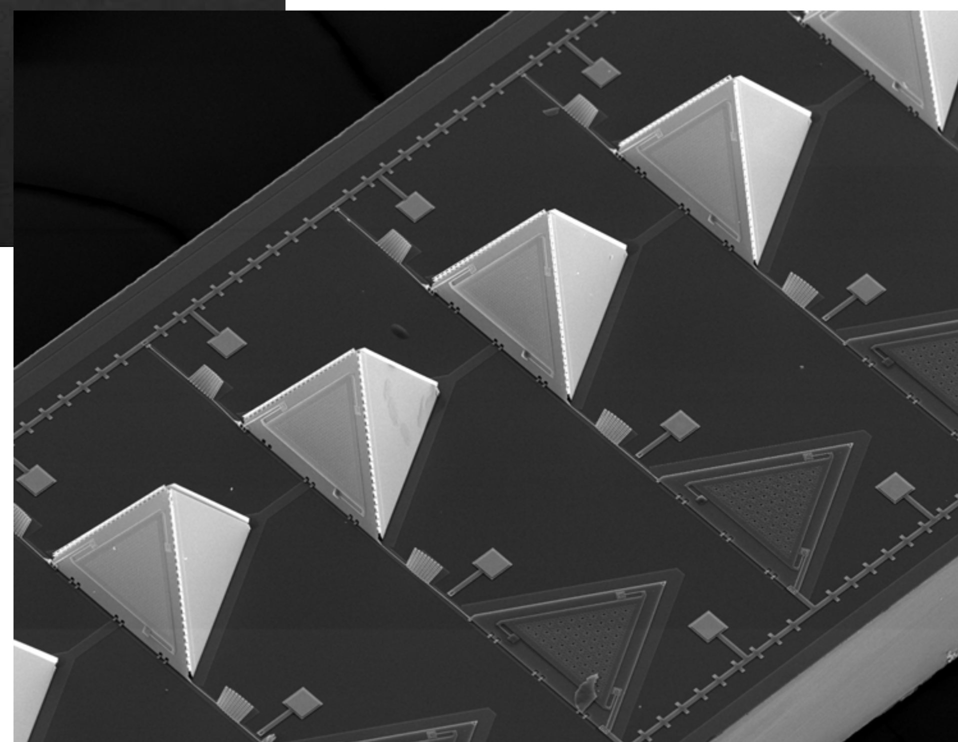
Ways to reduce MEMS noise (cont)

Coupling coefficient $\phi = \dfrac{SC_M V_o}{d}$

- Increase membrane compliance
- Increase the spacing (reduce viscous effects)
- Increase the microphone active capacitance
- Reduce stray capacitance
- Increase the size
- Use multiple microphone elements

MEMS microphone array





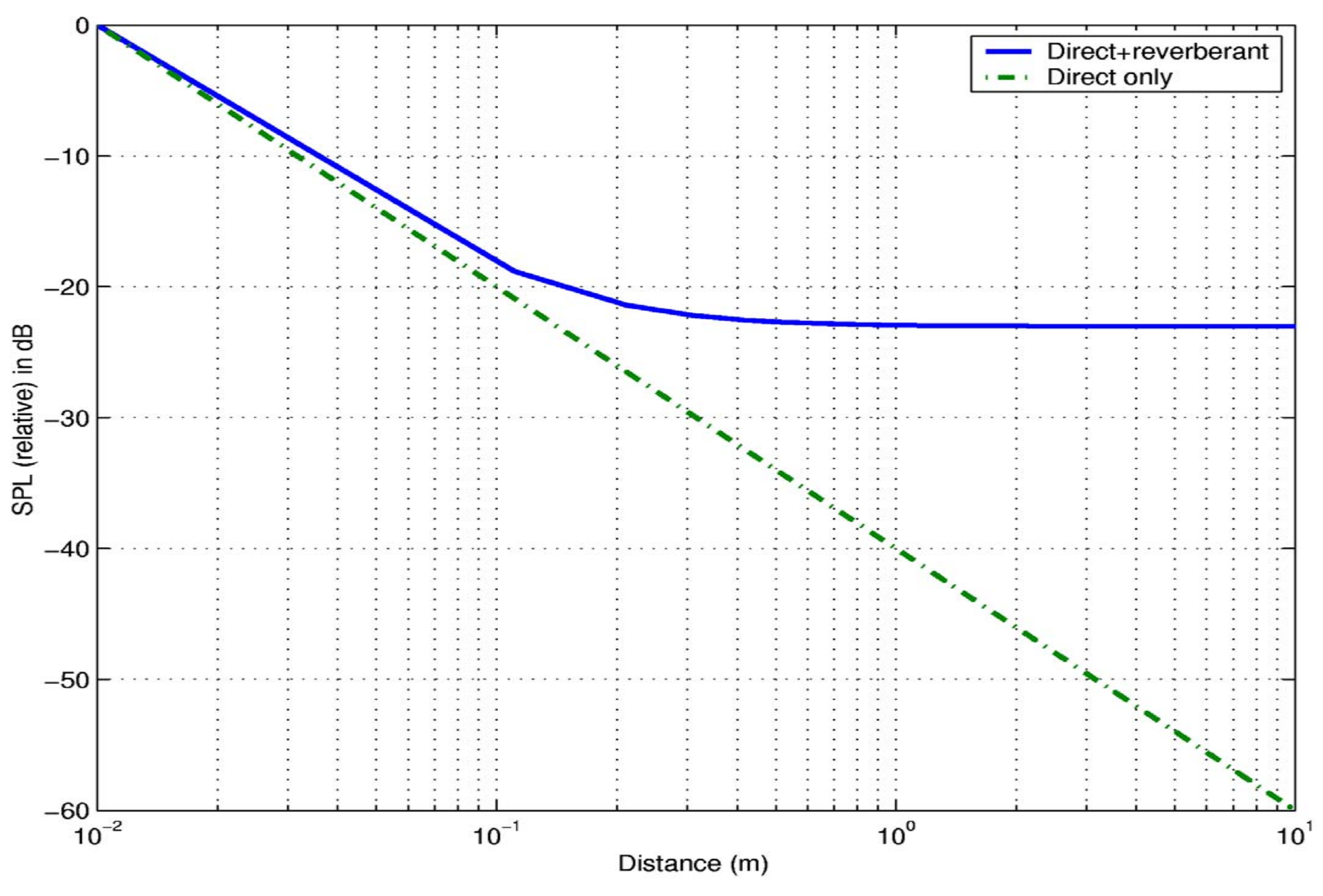
SNR gain: 10log(N)

(manually assembled)

Directional Microphones

Hearing aids, hands-free cell phones, PC’s and PDA’s now require directionality to improve speech SNR in noise and reverberation

SPL vs. distance



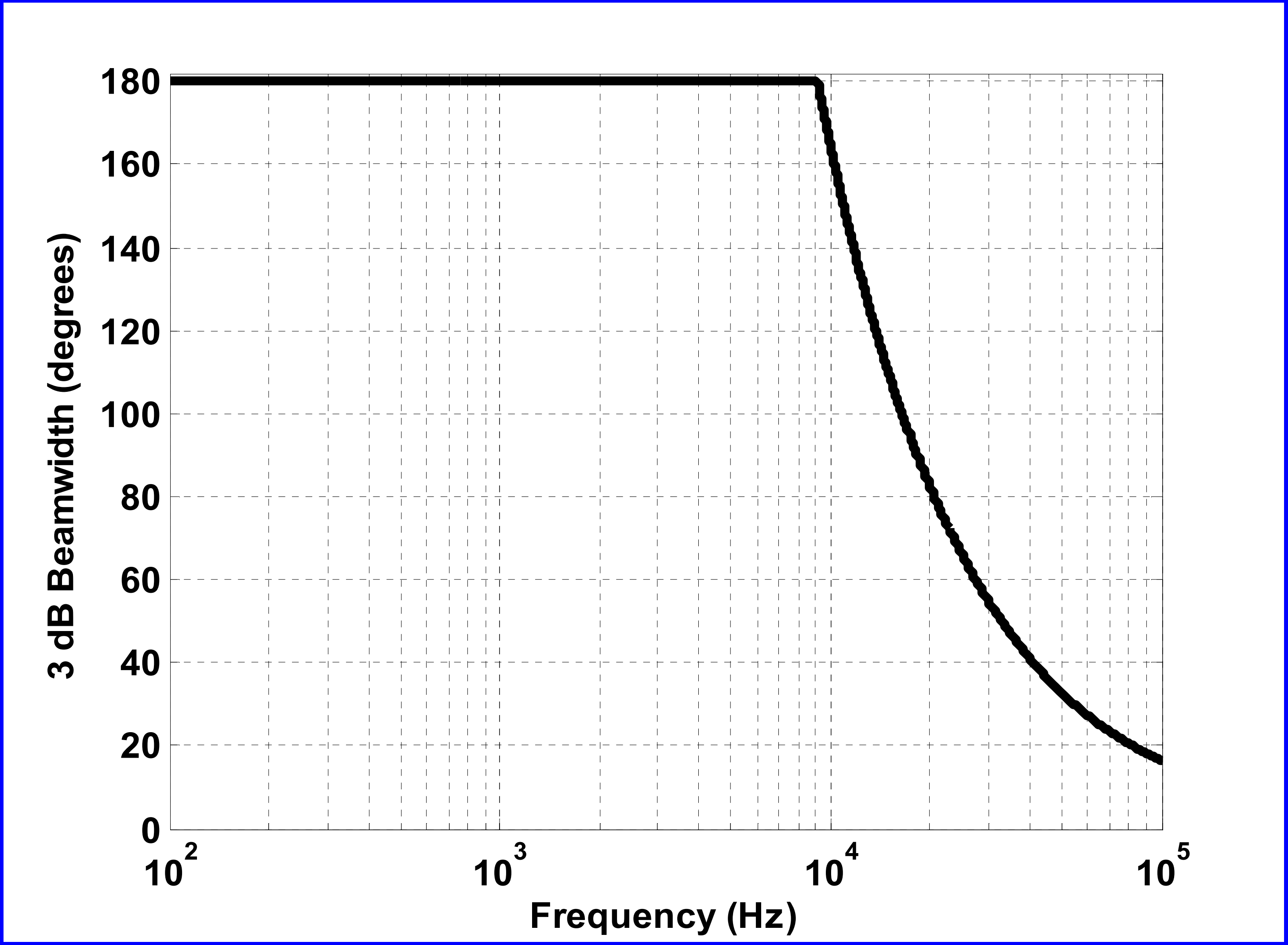
Can we build directional MEMS?

Linear Delay-Sum Beamformer?

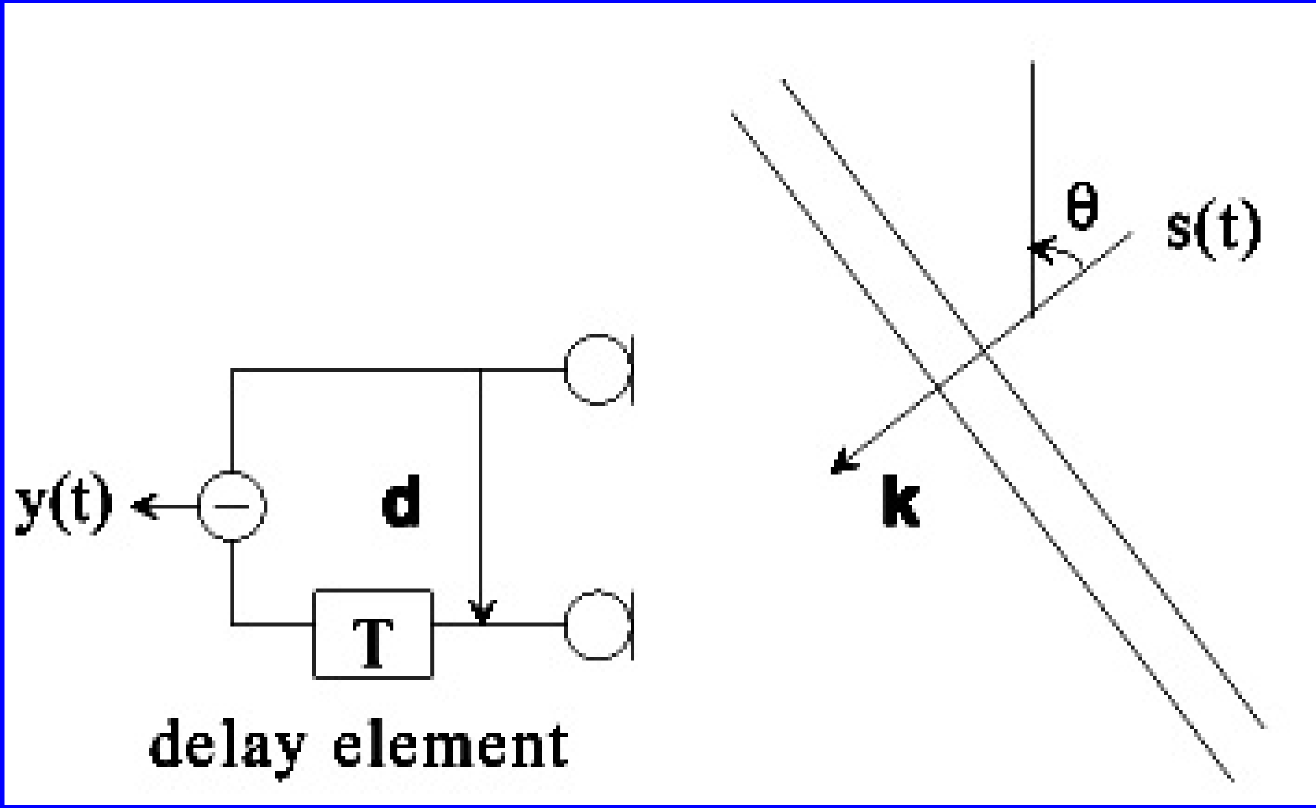
For a uniform linear array of N microphones, with spacing d_s, the 3 dB beamwidth is:

$$2\Delta\theta \approx 48^\circ \frac{\lambda}{N d_s}$$

For a 10 mm array:



differential microphone (first-order)



for small spacing , $kd << 1, \quad \omega T << 1$

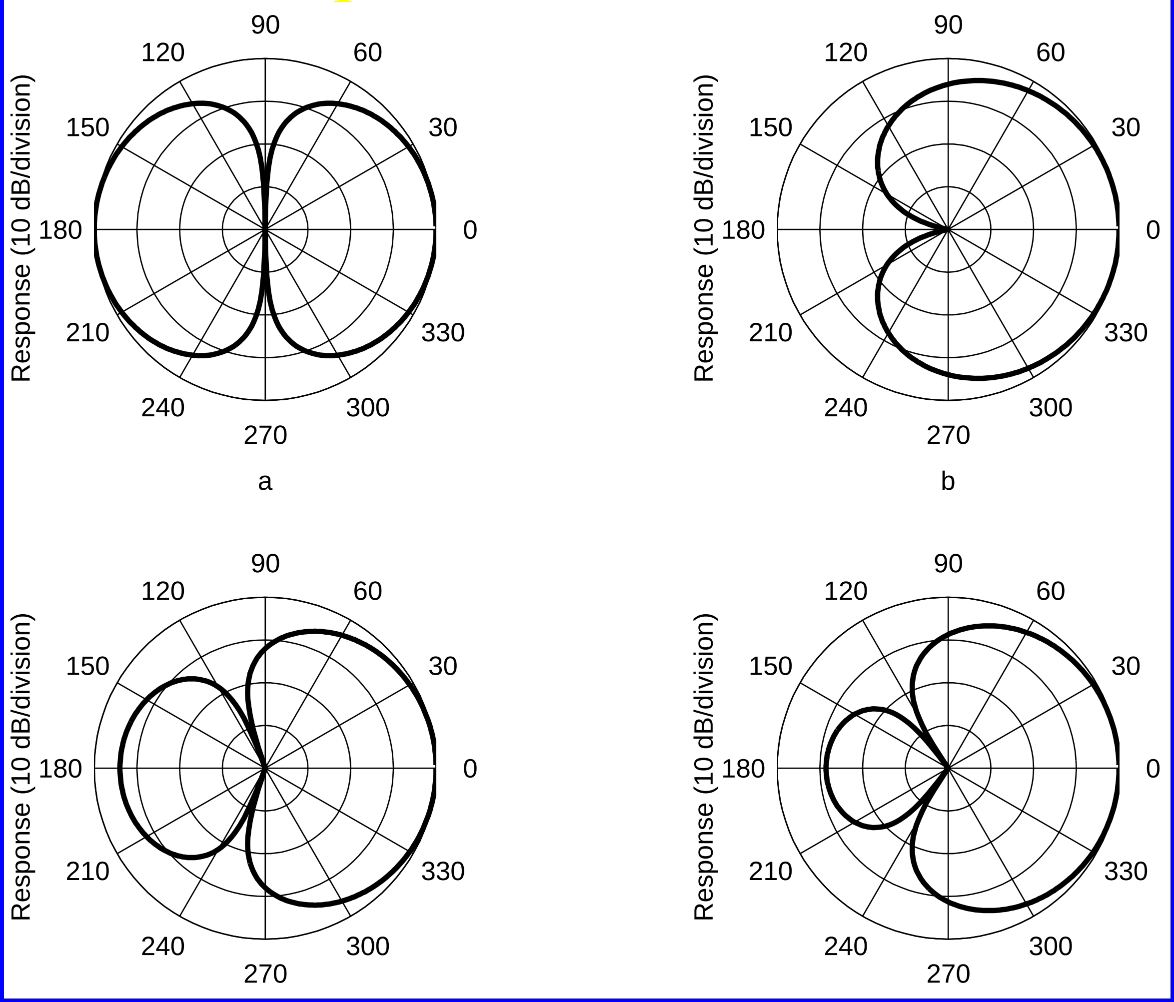
$$Y(\omega, \theta) \approx \omega S(\omega)[d \cos(\theta)/c + T]$$

Various first-order patterns

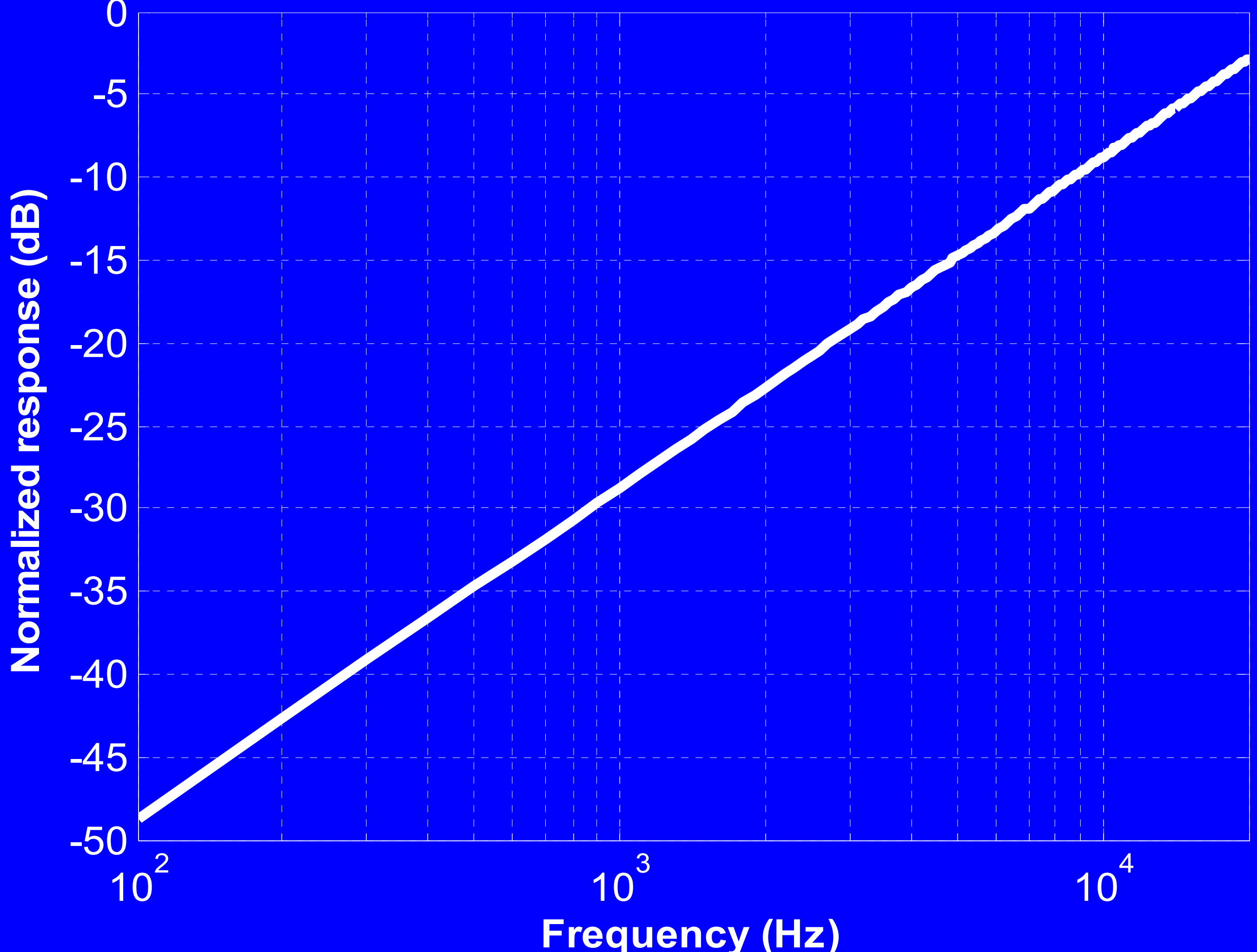
$$E(\theta) = \alpha + (1 - \alpha)\cos(\theta)$$

pressure

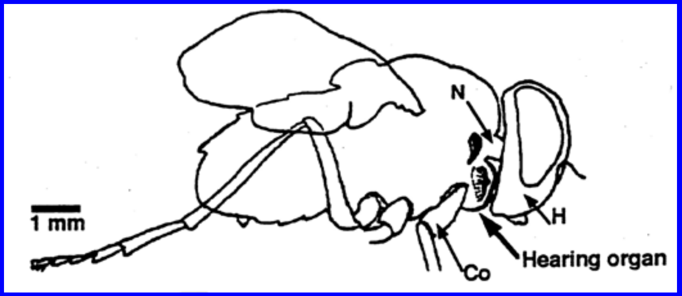
velocity

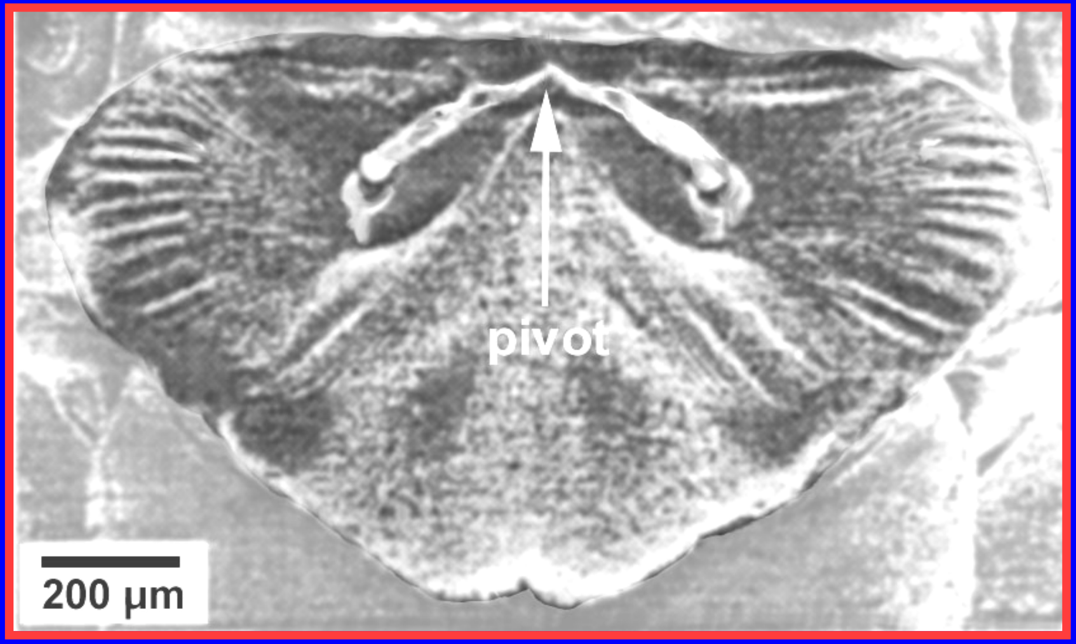


1 mm-spaced first-order pressure difference response

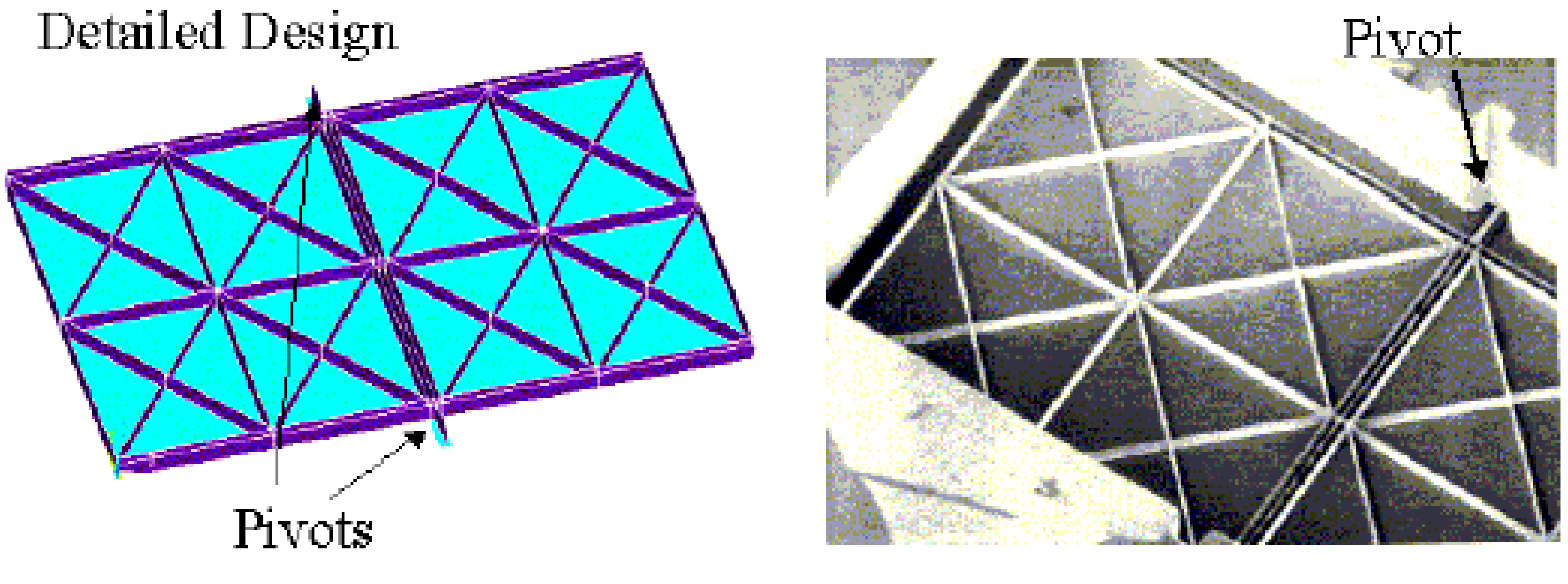


Differential directional microphone principle in nature (Ormia Fly)





SUNY Binghamton (Miles)



(a) FEA Model (b) Fabricated Polysilicon Device

1x2 mm diaphragm, 1μm thick

MEMS Microphone Summary

- Offers circuit integration and lower assembly cost
- Manufacturing precision → tighter specifications
- Thermal noise from a small gap a serious problem
- “Usable” microphones will have to be of mm size
- Back cavity required: 3D structures (self assembly) or bonding to another structure required
- Combinations of multiple pressure and/or different types of sensors and digital signal processing is a promising area for R&D