Exploring the latest MEMS trends and their impact on our Lives

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Yole Intelligence, part of Yole Group
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YOLE GROUP'S MAJOR ACTIVITIES PER ENTITY

Market, technology, and strategy consulting
M&A and evaluation of companies
Direct access to the analysts
Technology, process & cost analysis
Teardown and reverse engineering
Comparative analysis
Characterization of electro-optical performances and risks
Specification, design and industrialization of systems
FIELDS OF EXPERTISE COVERING THE SEMICONDUCTOR INDUSTRY

- Semiconductor Packaging
- Semiconductor Manufacturing
- Memory
- Computing and Software

- Photonics & Lighting
- Imaging
- Sensing & Actuating
- Display

- Radio Frequency
- Compound Semiconductors
- Power Electronics
- Batteries

- Electronic Systems
- Emerging Technologies
**FIRST OF ALL...SOME DEFINITIONS**

There is a wide variety of sensors and actuators. Only devices manufactured using deep etching, wafer bonding, or surface micro-machining on Silicon are considered MEMS.

<table>
<thead>
<tr>
<th>Category</th>
<th>MEMS</th>
<th>Not MEMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motion</td>
<td>MEMS accelerometers, gyros, IMUs</td>
<td>Piezoelectric accelero, Ring laser gyro, fiber-optic gyros, magnetic sensors...</td>
</tr>
<tr>
<td>Sound</td>
<td>MEMS microphones and MEMS microspeakers</td>
<td>Electret Condenser Microphone BA or EDS microspeakers...</td>
</tr>
<tr>
<td>Pressure</td>
<td>Capacitive or piezoresistive MEMS</td>
<td>Ceramic based, thin-film...</td>
</tr>
<tr>
<td>Environmental</td>
<td>MEMS gas sensors, flow meters, humidity sensors, environmental combos/hubs</td>
<td>Particulate matter sensors, electrochemical gas sensors...</td>
</tr>
<tr>
<td>Ultrasound</td>
<td>cMUT and pMUT</td>
<td>Bulk piezo/PZT (ceramics)</td>
</tr>
<tr>
<td>Microfluidics</td>
<td>Silicon Microfluidics</td>
<td>Microfluidics on glass substrates (passive functions)</td>
</tr>
<tr>
<td>IR</td>
<td>Thermopiles and Microbolometers</td>
<td>Bulk, pyroelectric IR sensor</td>
</tr>
<tr>
<td>RF &amp; Oscillators</td>
<td>BAW/FBAR/XBAR Silicon Oscillator or Resonator</td>
<td>SAW, TC-SAW Quartz Oscillator</td>
</tr>
<tr>
<td>Optical MEMS</td>
<td>MEMS Micromirrors: standalone, 1xN, NxN arrays and DLPs</td>
<td>Photonics (SiN, LN, etc.), waveguides</td>
</tr>
<tr>
<td>Others</td>
<td>MEMS OIS actuator, inkjet printheads, MEMS probe cards, other actuators</td>
<td>Proximity sensors, Ambient light sensors</td>
</tr>
</tbody>
</table>
SENSORIZATION – MEMS ARE UBIQUITOUS

Consumer
Smartphones, wearables, white goods, drones...

Automotive & mobility
Passenger cars, Light vehicles, e-bikes...

Industrial
AGV, robots / cobots, industrial motors, agriculture ...

Medical
Respiratory systems, surgical robots, Temperature monitor, smart patches...

Defense & aerospace
Soldiers, aircraft, satellites...

Telecom & infrastructure
Networks, Datacenters...

MEMS Engineer Forum 2023 | www.yolegroup.com
SMART SOCIETY – TOWARD SOCIETY 5.0

What does it mean in terms of technology?

✓ Sensors and smart devices
✓ Intelligence
✓ Connectivity

How MEMS technology could drive SMART Society goals?
MEGATRENDS RELATED TO MEMS ADOPTION

AR/VR
Voice HMI
Internet of voice

Mobile
5G
Hyperscale data centers
Connected factories

MEMS examples:
- Microphones, micromirrors, microspeakers, inertial sensors.
- RF MEMS, inertial sensors, micromirrors.
- Inertial sensors, micromirrors, pressure sensors.
- Inertial sensors, pressure sensors.
- Pressure, inertial sensors.

NEW USER INTERFACE

CONNECTIVITY

HEALTHY LIFESTYLE

GREEN ENERGY

EMBEDDED INTELLIGENCE

ROBOTIZATION

MEMS examples:
- Pressure, inertial, environmental, gas sensors, microfluidics, infrared imagers.

- Medical is meeting consumer for wellness applications.
- More wearable devices.
- Shift to PoC monitoring.
- Edge computing for smarter sensors.
- Predictive maintenance.
- Autonomous and robotic vehicles.
- Less waste, manufacturing optimization.
- EVs.

MEMS examples:
- Inertial sensors, pressure sensors.
- Inertial sensors, micromirrors, pressure sensors.
- Inertial sensors.
MEMS MARKET TRENDS OVERVIEW

MEMS market
$13.6B (2021) → $22+B (2027)

Traditional
- RF (BAW/FBAR)
- Si microfluidics
- Microphones
- Inertial

Emerging
- MEMS Timing
- Gas sensor
- Ultrasonic
- MEMS OIS
- Optical
- Microspeakers

Market/applications
- 5G
- TWS
- AR/VR
- Logistics
- Industry 4.0
- Automotive & Mobility (ADAS...)

MEMS Devices
MEMS MARKET FORECAST BY DEVICE

Revenues CAGR_{2021-2027}: 9%

2021 $13.6B

2027 $22.3B

CAGR_{2021-2027}: 9%
WORLDWIDE INFLATION ACROSS THE ENTIRE SUPPLY CHAIN

Increasing transport/logistics costs because of:
- New flight plans caused by the Ukraine/Russia war
- Increasing costs of energy (fuel)

With the pandemic, chip shortage, geopolitical tensions, and the Ukraine/Russia war, prices have kept increasing over the entire supply chain.

Strong over-demand and over-investment compared to supply have led to:
- Significant equipment price increases
- Delivery times increases

Higher operating costs are coming from:
- Workforce: higher wages for workers and operators + lack of talent
- Energy (electricity) prices sky-rocketing
- Increasing price of maintenance
- Manufacturing lines fully loaded (especially 8-inch)
- High cost of photolithography masks

Selling to:
- New customers?
- Long-term contract customers?

MEMS Players | Customers
---|---
Extra-costs

Long-term contracts

MEMS Players | Customers
---|---
Extra-costs

New contracts or short-term contracts
MEMS GROWTH OPPORTUNITIES

- MEMS OIS
- MEMS microspeakers
- Timing
- MEMS Gas Sensors
- Ultrasonic
- Optical MEMS
- RF MEMS
- Microphones
- Inertial combos
- Environmental
- Microfluidics

CAGR_{21-27}*

Revenue* ($M)

Device

2021 market value ($M)

2027 market value ($M)

* Log scales
OPTICAL MEMS MARKET TRENDS

**LiDAR**
- Automotive
  - 2D plane scanning
- Future mobility
  - 2D plane scanning
- 3D scanning
  - 2D plane scanning
- Smart factories (machine vision)
  - 2D plane scanning

**AR/VR**
- Projection
  - 2D plane scanning
- Eye-tracking
  - 2D plane scanning

**Telecommunications**
- Switching
  - 1 or 0 switching

**Spectrometer**
- Axial scanning
  - Single axis scanning
- Integrated interferometers

**Smart headlamps for cars**
- Light distribution control
  - 2D plane scanning
### OPTICAL MEMS TECHNOLOGY TRENDS

Three technologies for MEMS mirrors

<table>
<thead>
<tr>
<th>Electrostatic</th>
<th>Electromagnetic</th>
<th>Electrothermal</th>
<th>Piezoelectric</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Electrostatic" /></td>
<td><img src="image" alt="Electromagnetic" /></td>
<td><img src="image" alt="Electrothermal" /></td>
<td><img src="image" alt="Piezoelectric" /></td>
</tr>
</tbody>
</table>

**Electrostatic**

- *Players working on it:*
  - Preciseley Microtechnology Corp.
  - STI
  - Calient
  - Texas Instruments
  - Fraunhofer
  - Hamamatsu
  - Innoluce
  - Omnifabs

Electrostatic is a more mature technology, but there have been many developments in piezoelectric technologies.

**Electromagnetic**

- *Players working on it:*
  - STI
  - Maradin
  - Infineon

**Electrothermal**

- *Players working on it:*
  - Only research - no commercialized or advanced developed product

**Piezoelectric**

- *Players working on it:*
  - STI
  - STANLEY
  - SAL
  - Bosch

Invented for life
MEMS TIMING

MEMS timing attachment rate

RRH / AAU antennas

Communication devices: Router, Edge Server, Switches...

~ 8 MEMS timing units per antenna

Small Cells

~ 6 MEMS timing units per Small Cell

MEMS timing

WAN Routers

Servers

Switches

Storage

~ 6 MEMS timing units per device

Communication

Lidar

Smart Mirror

Infotainment

~ 6 MEMS timing units per device
MEMS OSCILLATOR TECHNOLOGY TRENDS

Source: SiTime

MEMS resonators encapsulated in silicon for high-reliability applications

~5% penetration rate of MEMS timing

replacement of the two quartz oscillators with one MEMS oscillator and deliver both kHz and MHz frequencies

Number of Timing (Units)

~ 40Bu ~ 60Bu ~70Bu

2017 2022 2027
MAGNETIC SENSORS
Automotive and electrification trends

Electrification pushes adoption of magnetic current sensors (high ASP)

ADAS and sensorization increases the overall number of magnetic sensors in cars

Position sensors are used for BTM due to electrification of cars

The number of hybrid vehicles increases, having both IC and electric engines

2017 $12.38 → 2021 $17.35 → 2027 $27.65

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AKM 3-axis compass magnetometer chip with Hall sensor in yellow and ASIC around it. Source: Yole System Plus

Courtesy of Lomaghesi
SENSORS FOR WEARABLES
Sensor's/Functionalities integration roadmap

Today

- Ambient light
- Microphones
- CMOS Image Sensors

Head

- ECG
- IMU
- Microphones
- Accelerometers
- Proximity sensors

Wrist

- IMU
- PPG (HR + SpO₂)
- Proximity sensors
- Pressure sensors
- Microphones
- Temperature sensors

Body

- ECG
- IMU
- Microphones
- 3D Sensors
- eCompass

+ MEMS Microspeakers
+ 3D Sensors
+ eCompass

2028

- + SpO₂ (PPG)
- + Blood pressure (PPG)
- + Ultrasound (command)
- + Temperature

- + PPG (blood pressure, SpO₂)

- + RF based monitoring

- + Blood pressure (PPG)
- + Ultrasound (command)
- + Galvanic skin response
- + CGM (RF, microneedles)

- + Galvanic skin response
- + Bioimpedance

2035

- + Vital sign monitoring
- + Microfluidics
- + Electrochemical detection (analytes), dehydration
- + CGM (optical detection)
- + Environmental combo

Data analysis and AI implementation
SENSORS FOR WEARABLE
Main markets targeted

Industrial use

Medical use

Consumer use

Accelerometers and gyroscopes, microphones

2022 $3.5B
$1.19B
$2.37B
$2.10B
$27M
$14M
$5.7B

CAGR 2022-2028: 8%

2028

7%

10%

9%

18
MEMS INDUSTRY STILL IN STRONG DEVELOPMENT PHASE

Fundraisings for MEMS players

Total raised: $>700M
MEMS INDUSTRY SIGNIFICANT DEVELOPMENTS
Status of innovative MEMS companies’ financial maturity (July 2021 – July 2022)

<table>
<thead>
<tr>
<th>Maturity</th>
<th>Time</th>
<th>TOTAL RAISED</th>
<th>MEAN VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-seed, seed</td>
<td>2018</td>
<td>$32M</td>
<td>$4M</td>
</tr>
<tr>
<td>Series A</td>
<td>2018</td>
<td>$138M</td>
<td>$11M</td>
</tr>
<tr>
<td>Series B</td>
<td>2020</td>
<td>$174M</td>
<td>$35M</td>
</tr>
<tr>
<td>Series C</td>
<td>2022</td>
<td>$412M</td>
<td>$137M</td>
</tr>
</tbody>
</table>

Companies with higher financial maturity will start driving the market in a few years.
MAIN TECHNOLOGY TRENDS – 3 PILLARS

Materials

Use of new materials, such as Piezo mainly (AlN, PZT), to boost performance, increase sensitivity, and decrease power consumption.

3D Integration

• MEMS post-processing
• 3D stacking with IC / Monolithic SoC
• 12” MEMS (cMUT from Butterfly, MEMSDrive/TSMC, Sai Micro 12” inertial rumors, Bosch will start production of MEMS on 300mm by 2026...)

Intelligence & Packaging

Past:
• Pre-processing (DSP), Sensor fusion
• WLC
• TSV/TGV
Now:
• Embedded SW/algos, AI on the Edge
• Heterogeneous integration

These trends are mainly related to adding more functionalities to the sensors.
MAIN MEMS DEVICES USING PIEZOMEMS TECHNOLOGIES

Volumes

Bunits

Munits

100kunits

10kunits

Markets introduction

= relative CAGR

PZT

RF MEMS
(BAW/FBAR/XBAR)

AlN/ScAlN

PZT

AlN/PZT

PZT

Microphones

Microspeakers

Micromirrors

Autofocus

pMUTs

Inkjet printheads
In the past, CMOS fabs moved from 6" to 8", then to 12", so MEMS used the remaining old equipment and capacity from outdated fabs. But now that CMOS fabs are remaining on 12" wafers, there is no leverage to buy old CMOS fab equipment, so new tools must be purchased.

However, no one wants to invest in a completely new line, as the development costs will be very high. If there is a move to 12", will the customers be ready to pay the price? Because the price will be higher due to increased cost per layer.

Nevertheless, Bosch announced in July 2022 that they would invest in new development centers and start the first production of MEMS devices on 300mm wafers in 2026. It will be exciting to see how the MEMS leader will move forward with this plan.
REDISTRIBUTION OF COMPUTING VALUE

Data value chain

1. Sensor raw data
2. Pre-processing
3. Processing
4. Computing
5. Analyzing

Traditional processing chain

- MEMS packaging
- MEMS
- ASIC
- AP/MCU
- Cloud

Edge-processing

- MEMS packaging
- MEMS
- ASIC + integrated DSP
- MCU

Specific to a sensor
Several sensors’ data inputs/outputs
Low latency, more safety, more privacy, i.e., no cloud computing used
A NEW PARADIGM SHIFT TO INCREASE THE SENSOR VALUE

Sensor value

Value decreases
Commoditization
Saturation
Data processing
Value increases
Computing (cloud/edge)
Value increases

Change Strategy or Business model or Acquisition

Examples (non-exhaustive)
- Cloud AI analytics
- ISPU product (AI on the edge)

Change of strategy: by 2030 phase out the automotive inertial MEMS business for active safety. Focus on intelligent sensors for industrial market & high-end IMU for navigation.
ATAKEAWAY

Smart society driven by MEMS technology or MEMS devices highly integrated in “Smart” devices? Chicken & egg rule!

MEMS are ubiquitous, used everywhere. The market is growing at a 9% CAGR, reaching >$22B in 5 years from now, but we could expect some slowdown in 2023 compared to 2022 due to inventory and ASP decrease.

Multiple secular trends in traditional devices (microphone, inertial, RF, etc) and emerging trends in emerging devices (micromirrors, gas sensors, ultrasonic, timing, microspeakers, etc) across various end-markets (consumer/TWS, automotive/ADAS, industry/logistics, etc).

Covid pandemic, chip shortage, geo-political situation, rising inflation, increased operational costs, etc are straining the MEMS supply chain.

Still >$700M fundraising for MEMS players last year and several players to follow in the coming years.

Use of new materials for new functions and new performances.

Transition to 12-inch wafers for MEMS ongoing?

General shift to more intelligent sensors and edge AI; MEMS leaders have released first products with embedded AI.
Thank you for listening, and if you have any question on the presentation or on related topics, don’t hesitate to contact me.

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And several other report and tracks from Yole SystemPlus