Other Ion Sources

Not: ECR, EBIS, RF, Fusion, Laser, MEVVA, Radioactive, Breeders, Medical, Multi-beam ...

What to do???
Ions for the industry

Ion Sources: the accelerators versus the industry

- Accelerators:
  Emittance, Intensity, Efficiency

- Industry:
  Throughput, Tunability, Cost
Ion Sources for Industry: the fields of use

- 1 - Focused Ion Beams:
  Focused Ion Beam for the nanotechnologies (FIB)
  Ion beam figuring for optical components (IBF)

- 2 - High Intensity Beams for MicroElectronics
  Ion Sources for implanters

- 3 - Broad Beam & “Ionic Machine” for the Industrial Coating
  Ion Source for Sputtering
  Magnetron discharge & End Hall ion source
Ion sources for the industry: *the orders of magnitude*

1 - High brightness ~ 1 nm-1 µm beam (FIB)
2 - High current ~ 1 cm-30 cm beam (Implanter)
3 - Broad beam ~ 30 cm- 10 m beam/treatment (Coating)
The good Units for the industrial purpose:

1 - Focused Ion Beam: $\mu m^3/s$

2 - Implanter: Wafers/h

3 - Coating: $\mu m/m^2/h$
Popular Ion Sources for the industry:

1 - Focused Ion Beams
   LMIS, RF, Microwave

2 - Implanters
   Freeman, Bernas

3 - Coatings
   Broad beam, Magnetron, Gridless
The purpose of the Focused Ion Beam systems:

- **1µm to 1 nm beam**
  - Milling
  - Imaging
  - Deposition
  - Lithography

- **1µA to 1 nA beam**
  - Doping
  - after 15 min KOH
The process with the Focused Ion Beam:

*Figure 4-8. 3D CAD drawing of a feature.*

*Figure 4-9. 3D FIB fabrication performed automatically from the CAD drawing in figure 8.*
The process with the Focused Ion Beam:

**Introduction**

Principle

- Surface modification due to interaction of impinging ions with the surface
- Elastic interaction
  - displacement, sputtering, defects, ion-implantation
- Inelastic interaction
  - secondary e	ext{-}, secondary ions, X-ray, photons γ

Moving the beam → Surface patterning
Other ion sources - Ions for the industry

1 - Focused Ion Beam for the Nanotechnologies
Other ion sources - Ions for the industry

1 - Focused Ion Beam for the Nanotechnologies

**Ion Source**

Liquid Metal Field Ionization Source (LMIS)

- High electrical fields at the apex of a rod leads to detachment of ions
- Liquid metal film is drawn into conical shape of the rod (W or Rh)
- Wide variety of ion species including Al, As, Au, B, Be, Cs, Cu, Ga, Ge, Fe, In, Li, Pb, Si, Sn, U, and Zn

![Diagram of LMIS](image)

Ga⁺ source from FEI
Other ion sources - Ions for the industry

1 - Focused Ion Beam for the Nanotechnologies

Ion Source

Liquid Metal Field Ionization Source (LMIS)

- Surface force \( F_s = 2 \frac{\gamma}{r} \) : surface tension inward force

- Coulomb force \( F_c = \frac{\varepsilon_0 E^2}{2} \), \( E = \frac{q}{4 \pi \varepsilon_0 r^2} \) outward force

- Maximum charge may be placed on the surface

  \( \Rightarrow \) Rayleigh limit:

  \( q_{Rh} = 8\pi \sqrt{\varepsilon_0/\gamma r^3} \)

  \( \varepsilon_0 = 8.85 \times 10^{-12} \) C²/J m dielectric constant

- Formation of Taylor Cone

\( \sim 20 \mu A. sr^{-1} \)

So useful current : some tens of nA max
Ion Source

Liquid Metal Field Ionization Source (LMIS)

Properties of metals used in LMIS

<table>
<thead>
<tr>
<th>Properties</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Low melting point</td>
<td>Minimise reaction between liquid and substrate</td>
</tr>
<tr>
<td>2 Low volatility at melting point</td>
<td>Conserves supply of metal; promotes long source life</td>
</tr>
<tr>
<td>3 Low surface free energy</td>
<td>Promotes flow of liquid and wetting of substrate</td>
</tr>
<tr>
<td>4 Low solubility in substrate</td>
<td>Dissolution of substrate alters the alloy composition</td>
</tr>
</tbody>
</table>
Other ion sources - Ions for the industry

1 - Focused Ion Beam for the Nanotechnologies

Ion Source

Liquid Metal Field Ionization Source (LMIS)

<table>
<thead>
<tr>
<th>Element</th>
<th>Melting point $T_m$ [K]</th>
<th>Boiling point $T_B$ [K]</th>
<th>Vapor pressure $p$ at $T_m$ [Torr]</th>
<th>$T$ at which $p = 10^{-6}$ mbar [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi</td>
<td>544</td>
<td>1832</td>
<td>$&lt; 10^{-8}$</td>
<td>672</td>
</tr>
<tr>
<td>Ga</td>
<td>310</td>
<td>2510</td>
<td>$&lt; 10^{-8}$</td>
<td>961</td>
</tr>
<tr>
<td>In</td>
<td>429</td>
<td>2364</td>
<td>$&lt; 10^{-8}$</td>
<td>877</td>
</tr>
<tr>
<td>Sn</td>
<td>505</td>
<td>2952</td>
<td>$&lt; 10^{-8}$</td>
<td>1070</td>
</tr>
<tr>
<td>Au</td>
<td>1336</td>
<td>2982</td>
<td>$\approx 10^{-4}$</td>
<td>1180</td>
</tr>
<tr>
<td>As</td>
<td>1090</td>
<td>886</td>
<td>$&lt; 1000$</td>
<td>423</td>
</tr>
</tbody>
</table>

Ion Source

Gas Field Ionisation Source (GFIS)

- atoms (molecules) are trapped by polarizations forces
- Trapped atoms hop on the surface until they are ionised
Ionisation: tunneling process with probability $D$:

$$D \propto e^{-c(l-\Phi)/V}$$

- $I$: Ionisation potential
- $\Phi$: Work function of emitter
- $V$: El. Potential
- $c$: constant

- Ions are ejected from the surface
Other ion sources - Ions for the industry

1 - Focused Ion Beam for the Nanotechnologies

Ion Source
Gas Field Ionisation Source (GFIS)

- Cooling the tip ⇒ higher residence time $\tau_r$ leads higher ionisation rate
- Ions: $H^+, He^+, Ne^+$, etc
- Low current $\frac{dI}{d\Omega} = 1 \mu A \text{ sr}^{-1}$ a)

\[ d\Omega = \sin \theta \, d\theta \, d\phi \]

$L = 1$

\[ a) \text{largest reported value (J. Orloff: High Resolution Focused Ion Beams, Kluwer Academic, 2003)} \]
Deposited films induced by focused ion beam

\[
W(CO)_6 (C_5H_4)CH_3Pt(CH_3)_3 \ldots
\]
Microwave source with “high brightness & high current” (µA): The COMIC concept

- $B_z$
- $B_{max}$
- $B_{ECR}$

Extraction plane

Area of maximum power coupling

Forward diffusion inside the magnetic field

~ $1/4 ~ 3 \text{ cm at } 2.45 \text{ GHz}$
Other ion sources - Ions for the industry

1 - Focused Ion Beam for the Nanotechnologies

Electric field amplitude distribution between the central antenna and couplers with quasi-coaxial geometry (COMSOL Calculation)

\[ f_{hf} = 2.45 \text{ GHz} \quad \text{Red} > 10^4 \text{ V/m} \]

Distribution of light in a Xenon discharge (2 W) between the central antenna and the coupler with quasi-coaxial geometry

\[ p \sim 10^{-2} \text{ mbar} \]
Other ion sources - Ions for the industry

1 - Focused Ion Beam for the Nanotechnologies

Electric field amplitude inside a closed cavity

Magnets

Extraction
Other ion sources - Ions for the industry

1 - Focused Ion Beam for the Nanotechnologies

Plasma source mode
(semi closed cavity)

Argon $10^{-2}$ mbar / 5 W

Source
20 KV

1st elect.
16 KV

Grounded electrode
0 KV

Ion source mode
(quasi closed cavity)

Nitrogen $5 \times 10^{-5}$ mbar / 5 W
~ 500 $\mu$A ~ 4 mA/cm$^2$
Reflected power (%) (below 5 W)

- Open circuit $P_r >> 50 \%$
- Matched load $P_r << 10 \%$

Current $I_c$

~ 3-5 %
Other ion sources - Ions for the industry

1 - Focused Ion Beam for the Nanotechnologies
Other ion sources - Ions for the industry

1 - Focused Ion Beam for the Nanotechnologies

- Focused Ion Beam for the Nanotechnologies

1.8 µAe total / 3 W / ext. 0.3 mm / 15 KV

129 130 131 132 134 136

1.2 mm.mrad

15 KV

3/10 mm ext.

1 σ

(12.5 KV élect. intermédiaire)
Other ion sources - Ions for the industry

1 - Focused Ion Beam for the Nanotechnologies

**LMIS**

- Source
- Virtual source $d_0$
- Emission surface $d$
- $\Omega$ Ion beam
- $V_{ext}$

**Virtual source size** ≈ 50 nm

$\alpha \approx 20^\circ$

Angular intensity ≈ 20 µA. sr-1

**Plasma source**

- Source
- Virtual source $d_0$
- $d$
- $\Omega$ Ion beam
- $V_{ext}$

**Virtual source size** ≈ 15 µm

$\alpha \approx 1^\circ$

Angular intensity ≈ 18 mA. sr-1
Other ion sources - Ions for the industry

1 - Focused Ion Beam for the Nanotechnologies

Source COMIC LPSC / Orsay Physics

I-FIB

Extractor electrode
Source Lens
DPA
Condenser lens
Aperture MVA
Wien Filter
Mass aperture MVA
Blanking
FC
Scanning octopoles
Objective lens
DPA
Sample
Other ion sources - Ions for the industry

1 - Focused Ion Beam for the Nanotechnologies

Microsurgery of an ant head with the COMIC source

100 x 100 x 100 μm³
15 hours with Ga (65 nA) = 40 minutes with Xe (1 μA)
The purpose of the Ion Beam Figuring:

**The beam**

- Mesure du profil d'érosion du faisceau
- Traitement mathématique sur ordinateur
- Mesure de la surface optique (par interférométrie)
- Simulation des erreurs résiduelles

**The pulverisation**

- Temps de séjour
- Trajectoires
- Séquence IBF sous vide (érosion des défauts)
- Mesure de la surface optique (contrôle)

Defaults:

- > 1 mm and
- < 1 µm
**Ion Beam Figuring machine:**

- **Before:** 2.93 nm RMS
- **After:** 0.19 nm RMS

+ No pressure: very thin optics
+ Determinist
- Under vacuum (heating)
- Rugosisy modification

**Mirror on x-y movement (for small curvature)**
Broad beam (20-40 mm) Kaufman filament source with grid extractor
Matching of the beam size to a characteristic length of the defaults:
Other ion sources - Ions for the industry

1 - Ion Beam Figuring of the Optic Industry

Ar – 150 µA – 1.4 KV – \( \sigma \approx 0.6 \) mm

High brightness gaussian millimeter beam size with COMIC
The purpose of the Implantation Technology:

- **High current**: ~ 10 mA acc.
- **Medium current**: ~ 1 mA acc.
- **Low current**

Φ 300 mm ~ 700 cm²

Standard requirement area 50-200 Kev

10¹⁴ at./cm²
The demand for the Implantation Technology:

Boron (z=5): BF$_3$, B$_2$H$_6$

Phosphorus (z=15): P(solid), PF$_3$, PH$_3$

Arsenic (z=33): AsH$_3$

gas

B, P, As

solid

TABLE 1

<table>
<thead>
<tr>
<th>SOURCE TYPE</th>
<th>PRIMARY SPECIES</th>
<th>AVERAGE ION BEAM CURRENT</th>
<th>SOURCE OPERATING HOURS</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENHANCED BERNAS</td>
<td>MIXED (As$^+$, P$^+$, B$^+$)</td>
<td>2-5mA</td>
<td>140-160 hrs.</td>
</tr>
<tr>
<td></td>
<td>MIXED (As$^+$, B$^+$)</td>
<td>~5mA</td>
<td>~80 hrs.</td>
</tr>
<tr>
<td></td>
<td>B$^+$</td>
<td>~10mA</td>
<td>~40 hrs.</td>
</tr>
<tr>
<td></td>
<td>As$^+$, P$^+$</td>
<td>~5mA</td>
<td>~140 hrs.</td>
</tr>
<tr>
<td></td>
<td>As$^+$, P$^+$</td>
<td>~10mA</td>
<td>~100 hrs.</td>
</tr>
<tr>
<td></td>
<td>Sb$^+$</td>
<td>5-10mA</td>
<td>40-50 hrs.</td>
</tr>
<tr>
<td>STANDARD FREEMAN</td>
<td>MIXED (As$^+$, P$^+$, B$^+$)</td>
<td>2-5mA</td>
<td>60-80 hrs.</td>
</tr>
<tr>
<td></td>
<td>MIXED (As$^+$, B$^+$)</td>
<td>~5mA</td>
<td>30-40 hrs.</td>
</tr>
<tr>
<td></td>
<td>B$^+$</td>
<td>~10mA</td>
<td>15-25 hrs.</td>
</tr>
<tr>
<td></td>
<td>As$^+$, P$^+$</td>
<td>~5mA</td>
<td>40-60 hrs.</td>
</tr>
<tr>
<td></td>
<td>As$^+$, P$^+$</td>
<td>~10mA</td>
<td>30-40 hrs.</td>
</tr>
<tr>
<td></td>
<td>Sb$^+$</td>
<td>5-10mA</td>
<td>20-40 hrs.</td>
</tr>
</tbody>
</table>
The purpose of the Implantation Technology:

- **Medium current**
  - Medium energy
  - **Wafer Process Station**

- **High current**
  - Medium energy
  - **Wafer Process Station**

- **High current**
  - Low energy
  - **Wafer Process Station**

**Other ion sources - Ions for the industry**

2 - High Intensity Beams for MicroElectronics
The purpose of the Implantation Technology: Ribbon beam generation

Scanning of a parallel beam

Generation of the ribbon beam
Other ion sources - Ions for the industry

2 - High Intensity Beams for MicroElectronics

The Freeman Ion Source:
The Bernas Ion Source:
The Indirectly Heated Cathode Ion Source (IHC):

Lifetime > 500 h
Strongly depending of the tuning
Other ion sources - Ions for the industry
2 - High Intensity Beams for MicroElectronics

The Indirectly Heated Cathode Ion Source (IHC):
High energy implantation: Negative ion source and Tamdem
High energy implantation: Positive ion source and Linac
Low energy implantation: Complex Molecular ion and Cluster

\[ \text{B}_{18}\text{H}_{22}, \text{C}_{16}\text{H}_{10} \]
followed by annealing (~1000°C)
Problems already open in the implantation technology:
(from A. Renau, Varian Semiconductor Equipment Associates
35 Dory Rd, Gloucester, Massachusetts 01930, USA, RSI, 81, 02B907, 8 February 2010)

1 - > 5 mA CW of $1^+$, $2^+$ & $3^+$ compact, low cost and upgradable

2 - > 5 mA CW of $B^-$, $P^-$, $As^-$ with lifetime > 168 h

3 - Large area implantation: < 1% over $\Phi$ 500 mm

4 - Low maintenance ion source
   (without modification inside the beam line optics)
The industrial field of use: the PVD coating
(Physical Vapor Deposition)

- Hardness modification (cutting tools, tribology)
- Solar (large area deposition)
- Optical component (laser and large optical mirror)
- Decorative coating (watchmaking,...)
Ionic modification of matériel:
The sputtering process: \((\text{Ar}^+, 5 \text{ kV at } 83^\circ / \text{surf.}, 2.5 \text{ ps})\)
Other ion sources - Ions for the industry

3 - Broad Beam & "Ionic Machine" for the Industrial Coating

\[ \text{Ar} \rightarrow \text{Si} \]
Other ion sources - Ions for the industry

3 - Broad Beam & "Ionic Machine" for the Industrial Coating

The Magnetron Sputtering (MS):

~ 300-700 V
~ 10⁻³ mbar
Ar
The Magnetron Sputtering (MS):
The Magnetron Sputtering (MS):
The Ion Beam Sputtering (IBS):

- **Vacuum box**
- **Substrate**
- **Targets**
- **Sample holder** (planetary motion)
- **Sputtered particles**

**Strong feedback contamination and maintenance**

**Broad beam ion source**
The Double Ion Beam Sputtering (DIBS) and assistance ion source:

- Vacuum box
- Substrate
- Assistance source
- Sample holder (planetary motion)
- Sputtered particles
- Substrate
- Sputtering source
- Targets

- $< 0.5 \text{ KV} > \sim 100 \text{ mA}$
- $2 \text{ KV} > 100 \text{ mA}$
The Double Ion Beam Sputerring (DIBS) and assistance ion source:
Other ion sources - Ions for the industry
3 - Broad Beam & "Ionic Machine" for the Industrial Coating

The RF broad beam “gridded”:

Fig. 3. Example of RF ion source, operating at 500 MHz, with four-grid ion extraction from a 600 × 300-mm plasma chamber (adapted from [40]).
Other ion sources - Ions for the industry
3 - Broad Beam & "Ionic Machine" for the Industrial Coating

The DC broad beam “gridded”:
Other ion sources - Ions for the industry

3 - Broad Beam & "Ionic Machine" for the Industrial Coating

The Microwave Linear ECR (2.45 GHz):

- Segmented grid system
- Discharge vessel
- 3 Microwave applicators with stub antenna
Other ion sources - Ions for the industry

3 - Broad Beam & "Ionic Machine" for the Industrial Coating

The industrial broad beam “gridless”:

(a) Ion-beam current.

Figure 2. End-Hall ion source schematic: 10 - ion source; 11 - ion beam; 12 - Hot Filament cathode; 13 - anode; 14 - magnetic system; 15 - gas distributor - reflector; 16 - magnet; 17 - holes for working gas supply; 18 - cathode supports; 19 - magnetic pole; 30 - dielectric separating plate; 35 - magnetic field lines; 36-37 - discharge channel.
The industrial broad beam “gridless”:
The industrial broad beam “gridless ion source”: Anode layer ion source / the reverse of the magnetron

For cleaning
Surface preparation
Etching
The Principle of multi beam devices:

Substrate

Flux on the substrate
Other ion sources - Ions for the industry

3 - Broad Beam & "Ionic Machine" for the Industrial Coating
**Other ion sources - Ions for the industry**

3 - Broad Beam & “Ionic Machine” for the Industrial Coating

**MBS-20**
inside 400 mm vacuum chamber

**Liner**
with substrate holder

200 mm
Cu Deposition on glass

70 mm
target holder

Cu Deposition on glass
Other ion sources - Ions for the industry

3 - Broad Beam & "Ionic Machine" for the Industrial Coating
3 - Broad Beam & "Ionic Machine" for the Industrial Coating

Cu on Si ( ~ 100 nm at ~ 100 nm /h)

263 +/- 7 nm
Profilometer measurements
Static substrate
Ta$_2$O$_5$ on Silicium
(Ta target under O$_2$)
Other ion sources - Ions for the industry

3 - Broad Beam & "Ionic Machine" for the Industrial Coating

Multi beam (10)
Multi target (Ta and C)
Multi current (25 and 500 µAe)

Simultaneous Argon beams on Ta and C targets
Conclusion

Ion Source for Industry: possible bridges between industry and accelerator technology

- 1 - Focused Ion Beams:
  High quality beam for AMS, radioactive ions, electrostatic acc.
  cyclotron injection, ...

- 2 - High Intensity Beams for MicroElectronics
  Knowhow for high intensity transportation
  Ion source for molecular ions ...

- 3 - Broad Beam & “Ionic Machine” for the Industrial Coating
  Multi beam machine for beam merging, superconducting material deposition, ...