Novel very low Energy Electron Sources – an Overview

Customized Accelerators
The Basis of a successful Application Development

EuCARD-2 Workshop with Industry
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Warsaw, Poland

Frank-Holm Rögner
Head of Department
Electron Beam Processes
Outline

- Electron Beam Basics
- Customized eBeam-Sources
- Summary
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- Customized eBeam-Sources
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Electron Beam Technology - Basics

Principles of electron beam generation and processing

- Cathode, emits electrons
- Acceleration anode
- Electromagnetic beam shaping, centering and stigmatic correction
- Pressure decoupling between electron generation and processing
- Electromagnetic beam focussing and fast deflection

Workpiece
Electron Beam Technology - Basics

Effect of Electron Beam Interaction

Thermal Processes
- Heat Production
  - Vacuum
    - Evaporation
    - Melting
    - Welding / Joining
    - Hardening
    - Micro-structuring

Non-thermal Processes
- Chemical Reactions
  - Atmosphere
    - Curing
    - Crosslinking
    - Drying print-inks
    - Surface modification (Grafting)

Biocidal Effects
- Atmosphere
  - Disinfection
  - Seed treatment
  - Sterilisation
  - Inactivation
  - Cell-modification
Outline

- Electron Beam Basics
- Customized eBeam-Sources
- Summary
Customized eBeam-Sources

The circle of technology development

- Industrial Demand
- EB Basic Hardware
- Technological Development
- Customized EB Hardware Development
- New Application
Electron Beam Technology - Applications

<table>
<thead>
<tr>
<th>Application</th>
<th>Power Range</th>
<th>Energy Range</th>
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<tr>
<td>Curing, Cross-linking,</td>
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Power [W]

Power density [W/cm²]
Applications – Welding, Structuring

- **Welding**: 15 – 180 keV
- **Hardening**: 10 – 80 keV
- **Curing, Cross-linking, Sterilization**: 20 – 10,000 keV
- **Melting**: 10 – 40 keV
- **Evaporation**: 10 – 80 keV
- **Structuring**: 20 – 150 keV
- **EBID, EBIE**: 20 – 50 keV
- **Melting**: 10 – 40 keV
- **Curing, Cross-linking, Sterilization**: 20 – 10,000 keV
- **Welding, Hardening**: 15 – 180 keV
- **Structuring**: 20 – 150 keV
- **EBID, EBIE**: 20 – 50 keV
Customized eBeam-Sources

**Thermionic Emitter**

- Axial gun CTW
  - 80 W – 10 kW
  - 40 – 70 kV

**Cold Cathode Emitter**
Low power axial gun – Basic ST 10/60

- Acceleration voltage
  40 … 60 kV

- Maximum beam power
  80 W … 10 kW

- Beam diameter
  15 … 500 µm

- Deflection field
  30 x 20 … 100 x 100 mm²

- Deflection frequency
  200 kHz
Micro-Welding: Customized eBeam-Source ST 2/70

Operation characteristic:
⇒ production plant

Technologies:
⇒ EB microwelding of mini sensors
  welding depth ≈ 750 μm,
  seam width ≈ 100 μm
⇒ EB microlabeling
  Structural width: ≥ 50 μm

Components:
⇒ EB gun ST 2 kW / 70 kV
⇒ HSS beam deflection unit
⇒ surface imaging and automatic beam alignment
  by backscattered electrons (RICO system)
⇒ Technology Package
Customized eBeam-Sources

**Thermionic Emitter**

- **Axial gun MEBW**
  - 2 kW

- **Axial gun CTW**
  - 80 W – 10 kW

**Cold Cathode Emitter**

- 60 kV

- 10 – 70 kV
Low power axial gun – Basic MEBW 60

- Supplier: Focus GmbH
- basic research in the field of electron beam micro-welding, engraving, structuring
- development of technologies for customer parts
- investigations regarding new applications of electron beam technology
- electron beam gun 2 kW / 60kV
- wide angel deflection ± 35°
- work pressure 5 x 10⁻⁴ mbar
- substrate size 150 x 150 x 150 mm
- 1 rotatable axis 0 … 32 min⁻¹
- short cycle times < 2 min
For this task, the electron beam has some **advantages** over the laser:

- Energetic electrons can penetrate thick metal layers with volumetric, adjustable absorption profile and with low energy reflection losses.

- High-power electron beam can economically be generated and operated in CW or pulsed mode.

- Inertia-less beam deflection enables very fast processing (goal: 7,200 8”-wafers / hour).

- EB-contact formation is a vacuum-based process. Therefore, it is per se compatible to vacuum deposition modules in a solar cell production line.

- Secondary effects (BSE, SE, X-ray, current probe…) can be used for process monitoring / quality control.
EBFC: Customized eBeam-Source

MEBW 60 - EmicPro

Development of next generation

- Pulsed high-voltage supply for fast modulation of beam power
- Optimized new developed cathode and anode for better beam quality and longer cathode-lifetime
- Development of electron-optics for micro-machining of large areas (deflection system, dynamic lenses, alignment, stigmator)
- Synchronization of all „beam-axes“ together with handling axes
Applications – Evaporation

- **Curing, Crosslinking, Sterilization**: 20 – 10,000 keV
- **Welding, Hardening**: 10 – 80 keV
- **Evaporation**: 10 – 80 keV
- **Structuring**: 20 – 150 keV
- **EBID, EBIE**: 20 – 50 keV

**Power** [W] vs. **Power density** [W/cm²]
Customized eBeam-Sources

Thermionic Emitter

- Axial gun MEBW
  2 kW
- Axial gun CTW
  80 W – 10 kW
- Axial gun ERIC
  60 – 300 kW

Cold Cathode Emitter

- 60 kV
- 10 – 70 kV
- 40 – 80 kV
High power axial gun – Basic ERIC 160/40

- Acceleration voltage: 40 kV
- Maximum beam power: 160 kW
- Beam diameter: app. 10 mm
- Deflection angle: 30°
- Deflection frequency: 3.5 kHz
ERIC eBeam System
EB system for Reactive Ion-aided Coating of large-area substrates at high rates

Development Goals:
- Coating Chamber Pressure ≤ 5 Pa
- Arc recovery time < 5 ms
- Acceleration voltage ≤ 60 kV
- Beam Power ≤ 300 kW
- Power Control
  - in space charge limited mode
  - in thermal saturation mode
- Automatic Centering / Focusing
- Scan frequency x/y ≤ 10 kHz @ 45°
- Dynamic Focusing ≤ 10 kHz @ 10%
- Extended cathode service life
**DVD-Process: Customized eBeam-Source ERIC-LVO 60/75**

**Customer’s Technology:**
- Directed Vapor Deposition (R&D / Pilot Scale)
- Application examples:
  - Thermal barrier & bond coatings
  - Hot corrosion resistant coatings

**FEP Components:**
- EB gun ERIC-LVO 60 kW / 75 kV
  - operation pressure $\leq 30$ Pa
  - deflection angle $\pm 30^\circ$
  - deflection frequency $\leq 3$ kHz
  - arc recovery time $\approx 5$ ms
  - MF high-voltage power supply
  - three-stage vacuum system
- Control system & Supply cabinet
Customized eBeam-Sources

Thermionic Emitter

- Axial gun MEBW
  - 2 kW
  - 60 kV

- Axial gun CTW
  - 80 W – 10 kW
  - 10 – 70 kV

- Axial gun ERIC
  - 60 – 300 kW
  - 40 – 80 kV

Cold Cathode Emitter

- Axial gun EasyBeam
  - 30 - 400 kW
  - 20 - 45 kV
Cold-Cathode EB Guns

Cold-Cathode Glow-Discharge Electron Beam sources for PVD -

Some Work Principles

- Inside the beam source, a high-voltage glow-discharge is sustained. The potential drop between cathode and anode occurs mainly across the cathode sheath. \((U = 10 \ldots 40 \text{ kV})\)

- Bombardment of the cathode by ions from the plasma generates secondary electrons (Emission current density up to 100 mA/cm²)

- Secondary electrons are accelerated through the cathode sheath ("transparent anode") - appropriate cathode contour promotes shaping of an Electron Beam with cross-over

- Then: Conventional electron optics applicable
# Fraunhofer FEP: High-Power Gun Series

<table>
<thead>
<tr>
<th>Type</th>
<th>EasyBeam</th>
<th>ERIC</th>
<th>ERIC-LVO</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acceleration Voltage</strong></td>
<td>30 ... 40 kV</td>
<td>40 ... 60 kV</td>
<td>75 ... 80 kV</td>
</tr>
<tr>
<td><strong>Beam Power</strong></td>
<td>30 ... 150 kW</td>
<td>60 ... 300 kW</td>
<td>60 ... 300 kW</td>
</tr>
<tr>
<td><strong>Coating Chamber Pressure</strong></td>
<td>≤ 1.0 Pa</td>
<td>≤ 5.0 Pa</td>
<td>≤ 50 Pa</td>
</tr>
<tr>
<td><strong>Flange Size</strong></td>
<td>NW 100 ... 160</td>
<td>NW 250</td>
<td>NW 250</td>
</tr>
<tr>
<td><strong>Turbo Pumps</strong></td>
<td>No</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>Roots Blower</strong></td>
<td>No</td>
<td>No</td>
<td>1</td>
</tr>
<tr>
<td><strong>Gun mounting angle</strong></td>
<td>0° ... 135°</td>
<td>0° ... 135°</td>
<td>0° ... 135°</td>
</tr>
<tr>
<td><strong>Beam Scan angle / frequency</strong></td>
<td>± 30° / 1 kHz</td>
<td>± 35° / 1 ... 10 kHz</td>
<td>± 35° / 1 ... 10 kHz</td>
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</table>
High-rate PVD: Customized eBeam-Source EasyBeam 120/40

“EasyBeam“ 60 kW / 30 kV
Beam Scanning: ±15°, \( f < 100 \text{ Hz} \)

“EasyBeam“ 120 kW / 40 kV
Beam Scanning: ±30°, \( f < 1 \text{ kHz} \)
Melt-refining + High-rate PVD: Customized eBeam-Source EasyBeam-Hybrid

The next generation - HYBRID CATHODE approach

“Merge the best of both worlds!”

Simplified design and supply, easy to control and to adjust

cold cathode plug with aluminum cathode

hybrid cathode plug with LaB$_6$ emitter in graphite holder

High acceleration voltage and power density, no cooling fluid
cathode plug with thermionic tungsten emitter
High-Voltage Glow-Discharge EB sources with Hybrid Cathodes

- Cooling water channels
- Ceramic isolator
- High-voltage feed-through
- Thermal isolation shield
- Graphite holder („Pierce“)
- Clamping fixture screw
- LaB$_6$ Emitter
- EB
- Glow-discharge Plasma (He or H$_2$ / NO oxygen!)

- Heating of the thermionic cathode
- Space charge compensation
- Purge gas for cathode chamber

(isolated against HV)
Applications – Curing, Crosslinking, Sterilization

- **Curing, Crosslinking, Sterilization**: 20 – 10,000 keV
- **Welding, Hardening**: 15 – 180 keV
- **Structuring**: 20 – 150 keV
- **EBID, EBIE**: 20 – 50 keV
- **Melting**: 10 – 50 keV
- **Evaporation**: 10 – 80 keV
### Thermionic Emitter

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<td>60 – 300 kW</td>
</tr>
<tr>
<td>Broadbeam FEPtron</td>
<td>30 kW</td>
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### Cold Cathode Emitter

<table>
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<td>PED gun 1 J per pulse</td>
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<tr>
<td>Axial gun EasyBeam 30 - 400 kW</td>
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High power linear gun – Basic  FEPtron 5/120

Linear type EB gun, high-vacuum inside

Cathode system

Electrons with energy  \( E_{\text{kin}} = e \cdot U_B \)

Electron exit window: A metal membrane between atmosphere and high vacuum

Electron curtain directed onto product

Product with treated border layer and untreated coating

transverse dose profile

maximal part width b

position along generator axis
Seed Treatment: Customized eBeam-Source FEPtron 30/150

Pilot Plant WESENITZ 2
- throughput 30 t/h
- chemical free seed treatment

FEP’s Low-Energy Technology allows to adapt acceleration voltage
⇒ improved dose homogeneity across layer
⇒ reduced loads of the carrier material
⇒ optimized investment costs

2D EB Systems available at FEP

<table>
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<tr>
<th>2D EB System type</th>
<th>Lab</th>
<th>Production I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration voltage (kV)</td>
<td>80 – 120</td>
<td>80 – 150</td>
</tr>
<tr>
<td>Layer thickness (µm)</td>
<td>10 – 60</td>
<td>10 – 120</td>
</tr>
<tr>
<td>Dynamic dose rate (kGy·m/min)</td>
<td>4 000</td>
<td>4 000 – 6 000</td>
</tr>
<tr>
<td>Transportation speed (m/min)</td>
<td>1 – 600</td>
<td>f (D)</td>
</tr>
<tr>
<td>Homogeneity of dose (%)</td>
<td>&lt; ±15</td>
<td>&lt; ±10</td>
</tr>
<tr>
<td>Working width (mm)</td>
<td>300</td>
<td>1 400</td>
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Electron treatment of surfaces

Treatment of seed or bulk goods

Surface sterilization of medical products

Lacquer curing on 3D-products

It would be nice to have a toroidal source for homogenous dose application onto 3D-surfaces
Electron treatment of surfaces

- Treatment of seed or bulk goods
- Surface sterilization of medical products
- Lacquer curing on 3D-products
Customized eBeam-Sources

**Thermionic Emitter**

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High-Voltage Glow-Discharge EB sources with Plasma Anode -

Issues: Dark-field Shielding

Solution:
Create an auxiliary low-pressure plasma for ion production
(Hollow Cathode or Wire Anode)

Toroidal EB source with Wire Anode Discharge Plasma

Numerical Simulation – Overview of Results

- Electron trajectories ⇒ Trapping
- Ion density distribution ⇒ Localization
- Distribution of electric potential ⇒ Repelling ions off the wires

Supply Voltage: 1 kV
**Customized eBeam-Sources**

**Thermionic Emitter**
- Axial gun MEBW
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  - 40 – 80 kV
- Axial gun Scanner
  - 2 kW
  - 150 kV
- Broadbeam FEPtron
  - 30 kW
  - 150 kV
- X-Ray gun
  - 10 kW
  - 150 kV

**Cold Cathode Emitter**
- 20 kV
- PED gun
  - 1 J per pulse
- 20 - 45 kV
- Axial gun EasyBeam
  - 30 - 400 kW
- 150 kV
- Toroidal gun TORES
  - 5 - ? kW
  - 150 kV
Fast 3D X-Ray: Customized eBeam-Source
ROFEX 10/150 (based on ROBOTGUN)

ROFEX – ROssendorf Fast Electron beam X-ray tomograph

Principle:

- electron gun
- focussing coils
- deflection coils
- electron beam
- target and X-ray detector
- test section

© Fraunhofer FEP
Ultra-fast X-ray computed tomography

- Basics:
  Fast deflected electron beam sources with sub-mm spot by FEP
- New technical application for investigation of multiphase fluid flow
- Interesting in boiling processes at power plant heating tubes and multi-phase fluids at petrol industry
- Possibility to get moved CT-pictures for fast dynamic investigation
- Cooperation in the field of ultra-fast X-ray detection with Institute of Safety Research, Helmholtz-Zentrum Dresden-Rossendorf

Low gas flow rate

High gas flow rate

5000 fps
### Customized eBeam-Sources

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- Summary
Summary

- Electron beam technology is an all-round tool for application in different branches

- Processing by electron beam means:
  - energy efficiency
  - very high processing speed
  - environmental friendly
  - long term stability
  - Vacuum or non-vac processing

- We are ready to develop your special electron beam technology
  - New applications require development of customized e-beam sources
  - New e-beam sources create ideas for new applications
  - Actually there are a lot of running development projects
Electron Beam Technology

Customized Sources – Your Benefit!

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