HIGH BRIGHTNESS METALJET X-RAY TECHNOLOGY FOR SEMICONDUCTOR PROCESS METROLOGY

NOW 25% BRIGHTER!

A conventional microfocus x-ray tube with the solid-metal anode replaced by a liquid-metal jet. The metal jet supports higher electron-beam power and can therefore generate higher x-ray flux.

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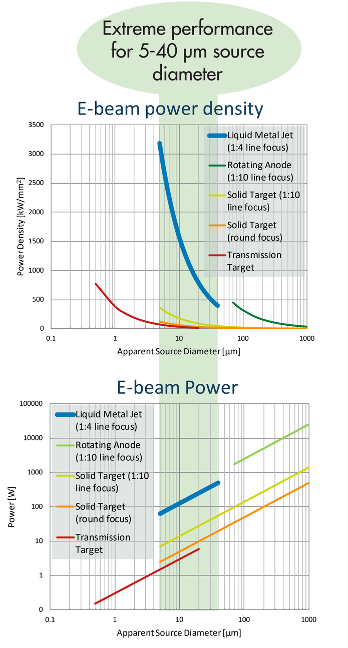
DETAILS

EXTREME BRIGHTNESS



POWER LOADING CAPABILITY

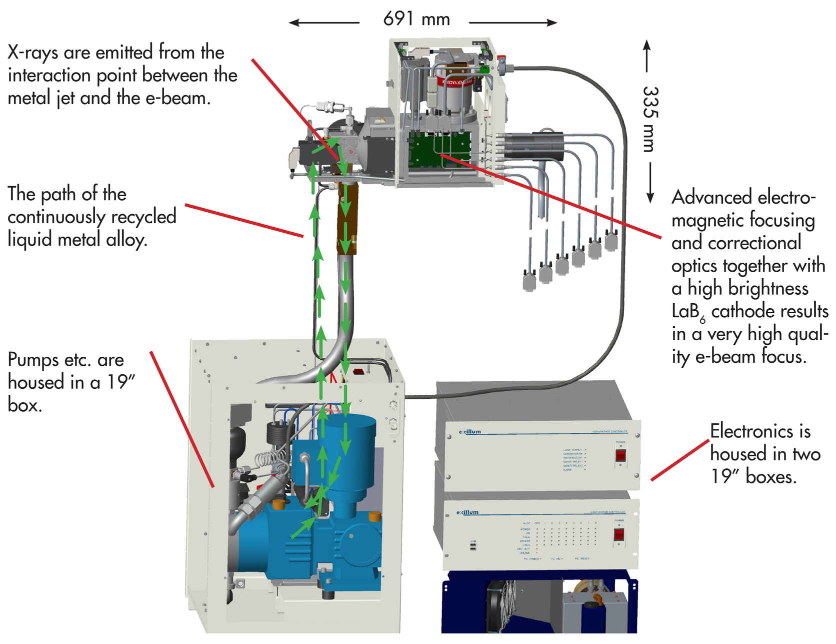
The x-ray power of all electron-impact x-ray generators is limited by the thermal power loading of the anode. In conventional solid anode technology, the surface temperature of the anode must be well below the melting point in order to avoid damage and this is fundamentally limited by the anode target material properties, primarily the melting point, the vapor pressure and especially the thermal conductivity. The liquid-metal anode is different since the limitation to maintain the target at well below melting point in removed. This is due to the fact that the material is already molten and that it is regenerative by nature, supplying new fresh target material at a rate of close to 100 m/s. This means that the electron beam and anode interaction may be destructive.

EXTREME BRIGHTNESS

Somewhat counter intuitively, the power loading capability of small-focus x-ray tubes roughly scale with the diameter and not the area of the e-beam focus. Therefore, the brightness is inversely proportional with the source diameter.

By combining extreme power loading capability and a small electron focus, a liquid-jet-source can achieve unprecedented brightness at micron spot sizes.

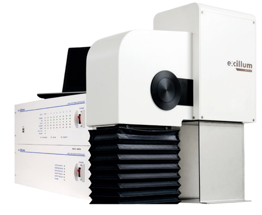
SOURCE SCHEMATICS



SOURCE SPECIFICATION

MetalJet D2+

The MetalJet D2+ is the third development of "off the shelf" commercially available liquid-metal-jet x-ray source. This is a fully radiation shielded dual port source with shutters. The source can be operated stand alone or is easily integrated.



MetalJet D2+ TECHNICAL SPECIFICATIONS

Cathode	LaB_6	Min. focal spot size	~5 μm
Target Material[1]	Ga or In rich alloy	Emission stability[3]	< 1%
Max current	4.3 mA	Position stability[3]	< 1 μm
Voltage[2]	10 - 70 kV / 160 kV	Min. focus-object distance[4]	18mm
Max. Power	250 W	Beam angle	13° or 30°

1) The room temperature liquid metal alloys supplied for the MetalJet source consist mainly of gallium, indium and tin. They have low reactivity and low toxicity but should be handled according to their safety data sheets and local regulations.
2) Depending on source version
3) Standard deviation
4) Without a shutter

PERFORMANCE EXAMPLES (Exally G1, 70kV)

Spot size[5] [μm, FWHM]	E-Beam Power [W]	Ga Kα Flux [Photons/(s·mrad²·line)]	Ga Kα Peak Brightness [Photons/(s·mm²·mrad²·line)]
10	125	7.5×10^6	5×10^{10}
20	250	1.5×10^7	3×10^{10}

5) Actual e-beam spot has a 1:4 aspect-ratio line focus, but the projected spot dimension is essentially circular. True round focal spots for, e.g., large-angle imaging can typically generate ¼ power compared to the numbers above.

X-RAY SPECTRA

X-RAY SPECTRA OF LIQUID METAL

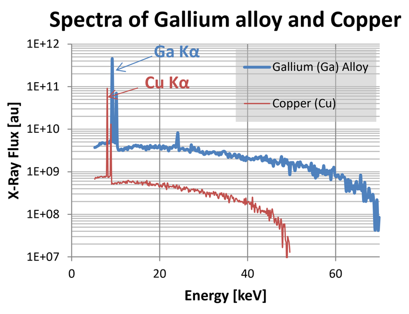
In order to reach different x-ray emission lines, different metal alloys are used. First generation metal-jet sources feature metal alloys that are molten at more or less room temperature. Still, several alloys have emission characteristics similar to regular solid anodes. Future upgrades can also include alloys with higher melting points.

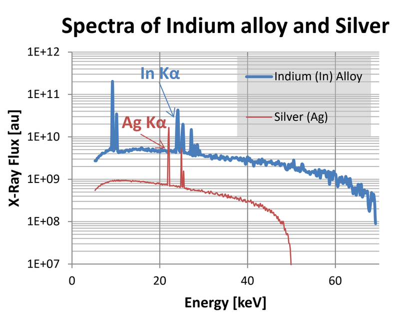
GALLIUM ALLOY

A gallium (Ga) rich alloy is available. It's 9.2 keV Kα emission line is close to the copper (Cu) Kα emission line.

INDIUM ALLOY

An indium (In) rich alloy is also available. It's 24.2 keV Kα emission line is close to the silver (Ag) Kα emission line.

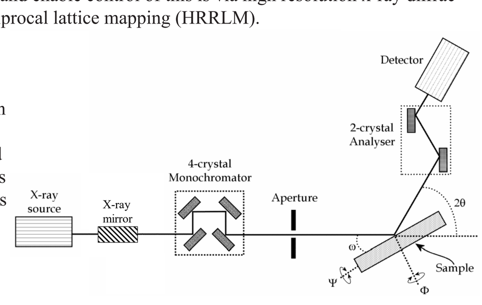




HIGH-RESOLUTION XRD

Various X-ray Diffraction (XRD) [1] techniques can benefit significantly from the high brightness achievable with the MetalJet X-ray source technology. This is becoming even more important as structures are going from planar to 3D as well as when device design involves the introduction of a variety of carrier mobility enhancement engineering such as channel alloying e.g. SiGe and/or strain, one of the few ways to measure and enable control of this is via high resolution x-ray diffraction (HRXRD) and high resolution reciprocal lattice mapping (HRRLM).

Current state of the art solid x-ray sources are far (several orders of magnitude) from achieving throughput even close to what the industry is requesting when metrology is needed on patterned wafers in production control [2]. This is truly highlighting the need of new types of high brightness sources such as the MetalJet X-ray source.



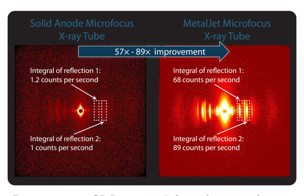
1. D. Bowen and B. Tanner, X-ray metrology in semiconductor manufacturing. Boca Raton: CRC/Taylor & Francis, 2006.

2. A. Schulze, 'X-Ray Metrology For The Semiconductor Industry', Int. Workshop on Compact EUV and X-ray Light Sources 2015.

SMALL ANGLE SCATTERING

STATE OF THE ART HOME LAB SCATTERING

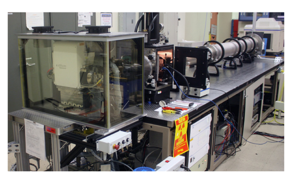
The MetalJet-technology is very well suited for Small Angle X-ray Scattering (SAXS), due to the small spot-size and high brightness. This has been proven in traditional SAXS, and in the figure below, you will find an comparison of different X-ray tubes, where rat tail tendon was studied.



Data courtesy of J. Lange, A. Schwamberger and K. Erlacher of Bruker-AXS.

CRITICAL DIMENSION-SAXS

Research on critical dimension small angle X-ray scattering (CD-SAXS) show that this technology could potentially complement and replace optically based CD tools as dimensions become smaller and more complicated. CD-SAXS can be performed both in reflection and transmission geometry. For transmission geometry energies higher than 20 keV are needed to get enough photons through the wafer for non-synchrotron CD-SAXS and early results with the MetalJet source technology and indium K-α emission at 24 keV show great promise towards meeting the requirement needs of the semiconductor industry. [1,2]



Example of CD-SAXS system with MetalJet at NIST, Gaithersburg.
Photo credit: Joe Kline, NIST

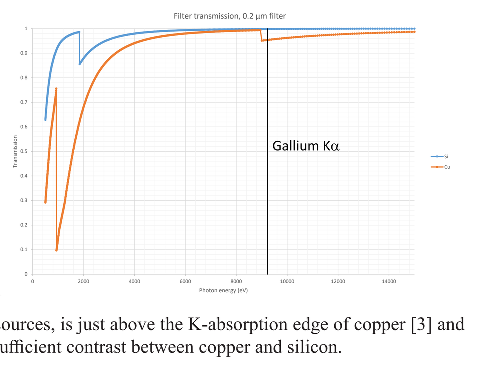
1. R. J. Kline, D. F. Sunday, D. Windover and W. Wu, 'Bringing CD-SAXS to the Fab', SEMICON West 2014, 2014.

2. M. Lapedus, 'Measuring Atoms And Beyond', Semiconductor Engineering Nov 21st

X-RAY MICROSCOPY

Traditionally the MetalJet-technology has been used extensively for phase-contrast imaging, both in propagation- and grating-based x-ray phase contrast imaging. The MetalJet-technology is very well suited for this type of imaging due to the fine spot-size and very high-brightness.

More recently, a growing interest in using the MetalJet-technology for imaging of nanoelectronics has emerged. The highest available resolution in lab-based X-ray microscopes is achieved with zone-plate based projection microscopes [2]. Such microscopes, however, typically use Cu Kα (~8 keV) radiation which is not so well suited to see copper structures in silicon due to poor contrast between copper and silicon at that energy. As illustrated by the graph to the right, the Kα of gallium, which is used in MetalJet sources, is just above the K-absorption edge of copper [3] and thus much better suited to create a sufficient contrast between copper and silicon.



2. T. Beetz, 'High-resolution X-ray Tomography Imaging Systems', CHESS Users' Meeting Ithaca, NY, 2008.

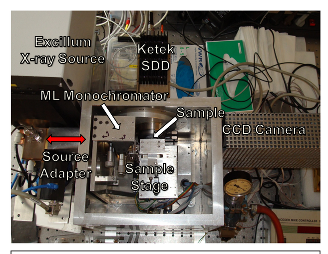
3. E. Gullikson, *Filter transmission*, http://henke.lbl.gov/optical_constants/filter2.html, visited on 2015-03-24.

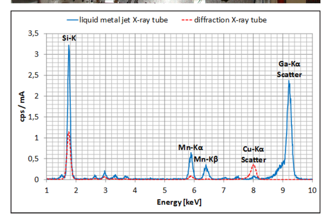
TXRF USING METALJET

Total reflection X-ray spectroscopy (TXRF) is a powerful analytical technique for qualitative and quantitative analysis of trace and ultra-trace elements in a sample. Historically several different x-ray sources has been used for this technique. A. Maderitsch et al. from Atominstitut, Vienna University of Technology, has performed TXRF-measurements with the MetalJet technology [4].

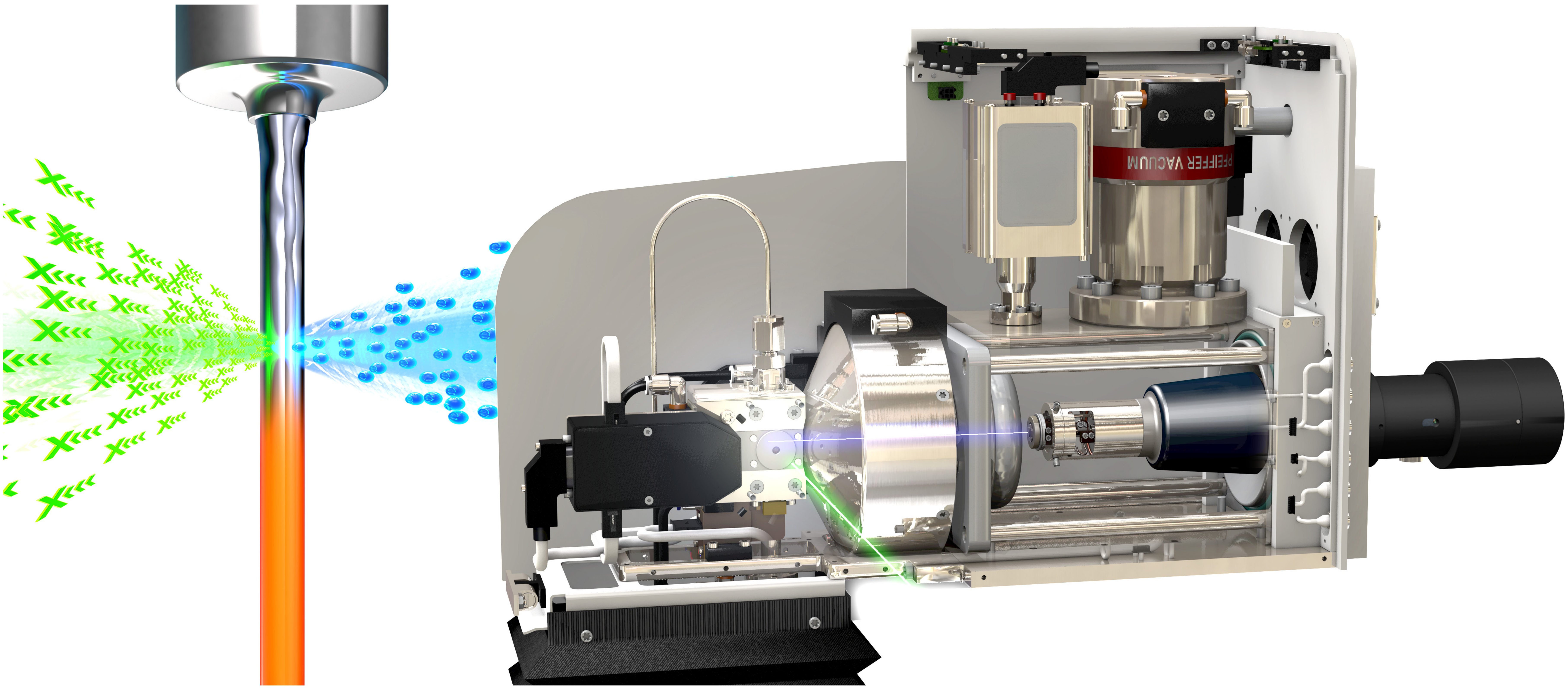
A TXRF spectrometer designed at the Atominstitut was adapted to the MetalJet, and several measurements were performed. As a reference, the same spectrometer was used with a 2 kW diffraction long fine focus x-ray tube (Cu-Kα). For comparison, the measurements were normalized to the x-ray tube current and to the counts per second (cps). The results are presented in the spectrum to the right.

The high brilliance of the MetalJet gives a great yield of the primary photons. Also, the normalized Mn signal is higher with the MetalJet, even though the excitation of Mn is better with Cu-Kα radiation.





4. A. Maderitsch, S. Smolek, P. Wobrauschek, C. Streli and P. Takman, Feasibility study of TXRF using a liquid metal jet X-Ray tube, Spectrochimica Acta Part B: Atomic Spectroscopy, TXRF2013 special issue



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