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Scanning Electron Microscopy Cathodoluminescence (SEM-CL)

Cathodoluminescence (CL) is the emission of photons from a material when it is excited by an electron beam.

In a Scanning Electron Microscope (SEM), the interaction between a focused probe of high-energy electrons and a sample gives rise to a variety of spatially resolved analytical signals. In certain types of samples such as semiconductors, insulators, and photonic structures, the interaction can produce visible light. This light is collected by specialized optics and put through a spectrometer where it is then captured on a CCD array detector. The emitted light provides insights into the sample's electronic structure, defect states, dopant and impurity distribution, crystalline quality, optical characteristics, and, in semiconductors, compositional variations through bandgap-related emission. Unlike conventional bulk optical characterization methods, SEM-CL offers nanometer-scale spatial resolution combined with full spectral analysis, enabling direct correlation between microstructural features and optical properties across a broad range of semiconductors and insulating materials.

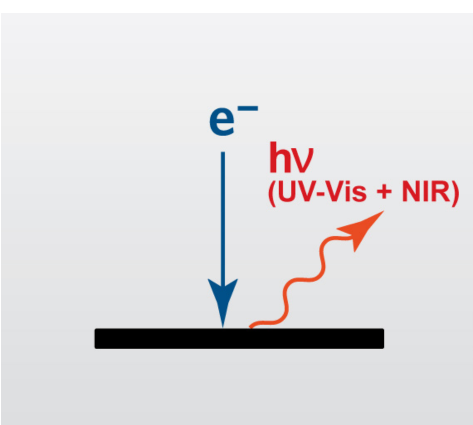

Figure 1. General schematic of how SEM-CL works

EAG has a highly specialized custom SEM-CL tool made by Attolight. The Attolight tool integrates CL detection directly into the SEM chamber, enabling:

- **Hyperspectral imaging**: Collecting full spectra at each pixel.
- **High collection efficiency**: Large on-axis parabolic mirror and optimized optics.
- **Cryogenic (LHe and LN_2) and Room-Temperature (RT) operation**: Highly stable temperature control capability.
- **Correlative imaging**: Overlaying CL maps with SEM images for structural context.
- Direct and indirect band gap materials possible

Strengths

- **Simple sample preparation either plan view or cross-section**: Cleaving, Broad Ion Beam, FIB, or P-FIB for XSing.
- **High spatial correlation**: CL is performed in an SEM, allowing direct correlation with electron imaging.
- **Non-destructive optical characterization**: Provides insight into electronic structure, defects, and bandgap variations without altering the sample.
- **Versatile material analysis**: Applicable to semiconductors, insulators, photonic structures, and geological samples.
- **Spectral sensitivity**: Enables wavelength-resolved analysis for identifying subtle composition changes, strain, impurities, defects, and recombination mechanisms.

- **Large field of view**: Compared to TEM-based CL, SEM allows imaging of relatively large areas (300x300µm max).

Limitations

- **Resolution constraints**: Limited by electron interaction volume (25-500nm), minority carrier diffusion length (nm-ums), and beam spot size (5-10nm).
- **Signal intensity**: Weak CL emission in some materials requires long acquisition times or high beam currents, which can cause beam damage.
- **Charging effects**: Non-conductive samples may require coating or low-voltage operation.
- **Temperature sensitivity**: CL intensity and spectra can vary with temperature, complicating interpretation.
- **Limited depth information**: CL is primarily surface/subsurface sensitive; deeper features may not be resolved.

Common Applications

- **Semiconductor characterization and failure analysis (FA)**: Mapping bandgap variations in GaN, SiC, or III-V materials and identifying threading dislocations. Dopant analysis.
- **LED and laser diode development**: Evaluating quantum well uniformity and emission wavelength.
- **Solar cell research**: Detecting recombination-active defects in perovskites or thin-film photovoltaics.
- **Geology and mineralogy**: Revealing growth zoning and trace element distribution in minerals.

Industry Sectors and Technologies

- Semiconductor and Microelectronics
- Optoelectronics - LED, Laser, and Photonics
- Solar Energy
- Geology

Case Study: FACELO AlGaN Epitaxy Analysis

Figure 2 shows SEM-CL data taken on a cleaved cross-section of an AlGaN on GaN FACELO sample. FACELO (Facet Controlled Epitaxial Lateral Overgrowth) is a growth strategy designed to enable high-Al-content AlGaN epitaxy on non-native substrates—such as GaN—without cracking, for use in UV lasers and LEDs. The process begins with a GaN substrate patterned with thin SiO_2 stripes. GaN epitaxy is then grown through the patterned windows, producing both lateral and vertical growth and forming an inclined interface. This initial growth creates a triangular cross-section, outlined by the white dashed line in the image.

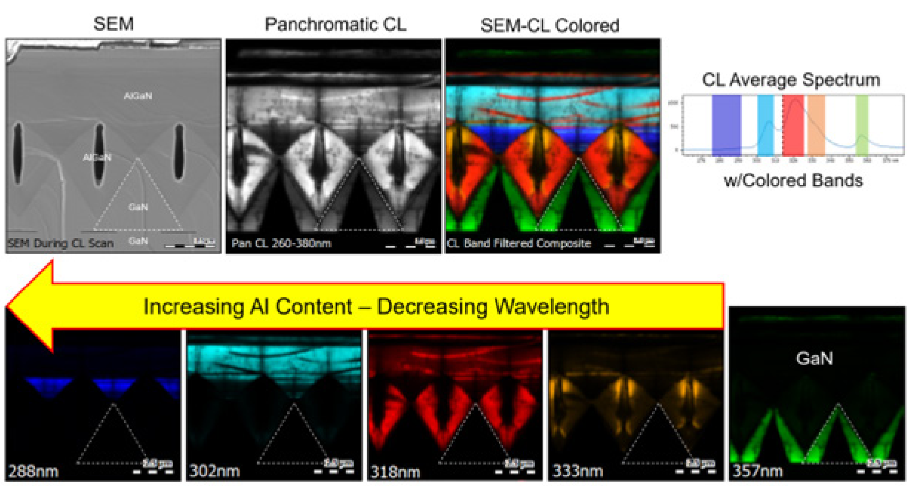

Figure 2. SEM-CL Analysis of AlGaN FACELO cleaved cross-section @ 10K

Subsequently, AlGaN is deposited on the inclined surface, eventually coalescing to allow the formation of multiple quantum wells (MQWs) near the surface. The top row of images shows the cleaved cross-section structure: an SEM secondary electron image, a panchromatic CL map (260–380 nm), and a colorized band-filtered composite with the corresponding average spectrum indicating wavelength ranges. The bottom row displays extracted monochromatic CL maps, from GaN (green, right) to high-Al-content AlGaN (dark blue, left).

SEM-CL demonstrates exceptional sensitivity, capable of tracking subtle Al composition variations (at% or better) as well as detecting dopants and contaminants (evident as bright regions within the dashed white lines of the original GaN epitaxy). This sensitivity makes SEM-CL a powerful tool for correlating structural and compositional information with electronic properties at the nanoscale.

Complementary Techniques

SEM-CL with STEM and APT for Highly-Localized Dopant-Level Analysis and Correlative Workflows

SEM-based cathodoluminescence (CL) offers both spatial and high compositional sensitivity, making it suitable for detecting even dopant-level variations. Historically, dopant analysis in semiconductors relies on Secondary Ion Mass Spectrometry (SIMS). For planar epitaxial structures, SIMS remains the gold standard for high-sensitivity depth profiling. However, SIMS lacks spatial resolution—its measurements average signals over large areas, which can obscure subtle inhomogeneities.

This is where SEM-CL excels. CL enables visualization of localized regions with differing electro-optical properties, providing a powerful tool for identifying variations in composition or defects. Once these regions are identified, they can be further examined using complementary techniques such as Scanning Transmission Electron Microscopy (STEM) for higher spatial resolution and crystallographic analysis. SEM-CL can even be performed on thin STEM lamellae before or after STEM imaging, allowing direct correlation of CL data with structural information from STEM. This combined approach delivers the best of both worlds: atomic-scale structural detail from STEM and compositional sensitivity from CL.

For ultimate nanoscale chemical analysis, Atom Probe Tomography (APT) is emerging as a transformative technique. APT provides 3D reconstructions with sub-nanometer spatial resolution and elemental sensitivity slightly lower than CL but significantly better than STEM-EDS or EELS. Together, SEM-CL, STEM, and APT form a complementary suite of tools for highly targeted advanced semiconductor, materials characterization and FA.

SEM-CL at EAG

Our SEM-CL scientists are highly educated, knowledgeable, and leaders in the analysis of a wide variety of luminescent materials. We pride ourselves in skillful sample preparation, knowledgeable spectral interpretation, and extensive experience with a wide variety of applications and complementary techniques. We utilize state of the art instrumentation to provide accurate data, written reports, fast turnaround times, and person to person service. Contact us today to learn how we can help.