The Academic
International Journal of Multidisciplinary Research

An Online Peer Reviewed / Refereed Journal
Volume 3 | Issue 6 | June 2025
ISSN: 2583-973X (Online)
Website: www.theacademic.in

Laser Induced Breakdown Spectroscopy (LIBS) for Materials Characterization: Mechanisms and Challenges

N. N. Gosai

Associate Professor, Department of Nanoscience and Advanced Materials, Saurashtra University, Rajkot 360 005, Gujarat, India. Author E- Mail : nitin_gosai86@yahoo.com

DOI : https://doi.org/10.5281/zenodo.15857773

ARTICLE DETAILS

Research Paper

Accepted: 27-06-2025

Published: 10-07-2025

Keywords:

Laser induced breakdown spectroscopy (LIBS), Light Matter interaction, Atomic spectroscopy.

ABSTRACT

Laser induced breakdown spectroscopy (LIBS) plays most important role in materials characterization and it has been emerged as a versatile diagnostic tool for elemental analysis in solid state systems, especially under ambient or in situ conditions. Comparatively high power of laser beam is incident / ablates onto the material and the induced plasma has been characterized in order to check / inspect elemental characteristic. This review article examines the physical mechanisms underlying LIBS, recent developments in plasma diagnostics and spectroscopic interpretation, and its applications in the context of modern materials science. Laser and matter interaction, plasma evolution, and material specific ablation responses plays an important role. The role of LIBS in characterizing complex oxides, low-dimensional systems, and disordered materials is discussed in the context of current challenges, such as sensitivity limitations, matrix effects, and quantitative calibration and integration with other surface sensitive techniques are outlined in the present review paper

1. Introduction

Laser induced breakdown spectroscopy (LIBS) utilizes a high intensity pulsed laser to induce localized ablation and plasma formation (called micro plasma), followed by time resolved optical emission spectroscopy. Emission from excited atoms and ions has to be analysed spectral point of view and hence it will give idea about elemental composition point of view about the target material. It offers rapid, multi elemental detection with minimal sample preparation and is compatible with a variety of condensed matter systems. This is useful for target which is having in form of solid, liquid or gaseous form as well as this technique required almost no sample preparation technique or it is minimal. While originally adopted for geochemical and environmental analysis, LIBS has gained increasing attention in the solid-state physics community due to its applicability to nanostructured materials, heterostructures, and high entropy alloys. It is not useful only for materials identification / characterization, but it is also useful in mining and geology, environmental monitoring and assessment and space exploration and in so many area of science and technology.

In this review, author provides a framework to understand LIBS from a physics standpoint, focusing on material laser coupling, non equilibrium plasma dynamics, and emission mechanisms. Author also summarizes the technique's applicability and limitations in emerging materials systems.

2. Laser Matter Interaction in Condensed Phases

2.1 Optical Absorption and Energy Deposition

Common or primarily Nd YAG Lasers natural / fundamental / primary 1064 nm which is having 532 nm, 355 nm and 266 nm as harmonic / overtone of the wavelength has been widely used to perform the operation in LIBS. The laser energy is absorbed via multiphoton ionization and avalanche processes, leading to material breakdown. For ultrashort pulses (<10 ps), nonthermal mechanisms dominate, while longer pulses (>10 ns) induce significant thermal diffusion. It is clear that in such case, longer wavelength (lower energy of laser pulses) is having good penetration depth over materials target but it will leads more thermally induced defects in specimen. Shorter wavelength (higher energy of laser pulses) will able to produce hotter and denser plasma from the target materials and it will lead to high resolution as well as sensitive detection point of view.

2.2 Ablation and Plasma Formation

Material ejection follows phase explosion or Coulomb explosion, depending on fluence and pulse width. The resulting plasma evolves under the influence of density gradients, radiative losses, and electron-ion recombination. These processes strongly depend on lattice structure, bandgap, and thermal conductivity of the target.

3. Plasma Diagnostics and Emission Physics

3.1 Plasma Temperature and Electron Density

Quantitative LIBS analysis requires accurate modeling of the plasma state. Boltzmann plots, Stark broadening, and Saha–Boltzmann equilibrium models are used to derive local thermodynamic parameters. Deviations from local thermodynamic equilibrium (LTE) occur especially in femtosecond LIBS or low-pressure environments.

3.2 Emission Line Analysis

Transition line intensities and broadening mechanisms are influenced by self-absorption, pressure broadening, and collisional redistribution. Spectral resolution and detection timing (gate delay) are critical in extracting reliable elemental signatures.

4. LIBS in Advanced Materials Systems

4.1 Thin Films and 2D Materials

LIBS has been applied to analyze stoichiometry and depth profiles in complex oxides (e.g., $SrTiO_3$, $YBa_2Cu_3O_7$), chalcogenides, and graphene-related materials. However, damage thresholds and surface morphology effects complicate reproducibility.

4.2 Disordered and Amorphous Solids

In glasses and amorphous semiconductors, the absence of long-range order influences ablation threshold and plasma plume dynamics. LIBS offers unique insight into dopant distribution and heterogeneity. LIBS combined with depth-resolved profiling has been used to examine interfacial diffusion, compositional gradients, and degradation in multi-layered devices (e.g., perovskite solar cells).

5. Ultrafast and Hybrid LIBS

Recent trends include

- Femtosecond LIBS: reduced thermal damage and better spatial resolution
- Dual-pulse LIBS: enhanced signal via second delayed pulse
- LIBS–Raman, LIBS–XPS hybrids: combined chemical and structural analysis
- LIBS under controlled atmosphere/vacuum for improved reproducibility

6. Current Challenges

- Sensitivity: Light elements (H, Li, Be) remain difficult to detect reliably.
- Quantification: Lack of standards in complex materials hampers accuracy.
- Plasma modeling: Non-LTE and complex expansion dynamics are not fully understood.
- Surface effects: Surface roughness and oxidation can dominate spectral response.

7. Future Outlook

Advances in ultrafast laser sources, high-speed detectors, and data science are poised to transform LIBS into a high-precision tool for solid-state physics. Potential directions include:

- Real-time process monitoring in epitaxial growth
- Miniaturization as well as portability
- Industrial automation in smart manufacturing system
- Improved qualitative analysis like calibration free LIBS (CF LIBS)
- In situ LIBS in UHV or cryogenic environments
- It can be coupled / integrated with other techniques like LIDAR, ICP MS, Raman Spectroscopy and many other.
- AI-assisted spectral deconvolution
- LIBS as a feedback tool for additive manufacturing

References

- D.A. Cremers, L.J. Radziemski, *Handbook of Laser-Induced Breakdown Spectroscopy*, Wiley (2006).
- M. Baudelet (Ed.), *Laser-Induced Breakdown Spectroscopy: Theoretical and Experimental Aspects*, Elsevier (2016).
- J. Hermann et al., *Spectrochim. Acta B*, **63**, 1–30 (2008).
- C. Dong et al., *Appl. Phys. Lett.*, **105**, 131603 (2014).
- A. De Giacomo et al., *J. Anal. At. Spectrom.*, **29**, 2204 (2014).