JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

SUPERCONDUCTIVITY AT ROOM TEMPERATURE: PROGRESS AND CHALLENGES

***Dr. Rajkumar Hosdodde,**
Associate Professor, Department of Physics, Government First Grade College for Women BIDAR.

Abstract:

Room-temperature superconductivity represents one of the most significant frontiers in condensed matter physics and materials science. In recent years, hydrogen-rich compounds synthesized under extreme pressures have achieved superconducting transition temperatures exceeding 250 K, edging close to practical "room temperature." These advances stem from the synergy of first-principles calculations, high-pressure synthesis in diamond anvil cells, and increasingly sophisticated characterization techniques. While such progress demonstrates that conventional electron–phonon mechanisms can support remarkably high critical temperatures, challenges remain. The most pressing issues are the need for megabar pressures to stabilize these phases, the limited reproducibility of experimental results, and the engineering hurdles associated with scaling from micron-sized samples to usable conductors. Controversies over data integrity in certain high-profile claims have underscored the importance of reproducibility, multi-probe verification, and open data sharing. Beyond the physics, the broader challenge lies in translating breakthroughs into ambient-pressure, manufacturable, and chemically stable materials suitable for technological deployment. Research is now focusing on chemical precompression strategies, metastable phase stabilization, and hybrid design approaches that combine hydrogen with light elements such as carbon or boron. If successful, room-temperature superconductors could transform power transmission, magnet technology, and computing. However, the timeline for usable materials remains uncertain, requiring both fundamental discovery and long-term engineering development.

***Keywords**: Superconductivity, Room Temperature, Hydrides, High Pressure, Electron–Phonon Coupling, Materials Design.*

INTRODUCTION:

Superconductivity is a state of matter in which a material conducts electricity without any resistance. In this phase, electrons form pairs, known as Cooper pairs, that move coherently through the crystal lattice without scattering. As a result, current can flow indefinitely without energy loss. Superconductors also expel magnetic fields, a phenomenon known as the Meissner effect, making them valuable for applications such as powerful magnets, medical imaging, and energy-efficient power transmission. Traditionally, superconductivity has been observed only at very low temperatures, often requiring cooling with liquid helium or nitrogen.

"Room temperature" in scientific discussions refers to a temperature close to everyday ambient conditions, usually around 20–25 °C (293–298 K). In the context of superconductivity research, the phrase "room-temperature superconductivity" implies the achievement of superconducting behavior at or above these values. This distinction is important because eliminating the need for expensive cryogenic cooling could make superconducting technologies far more practical and widespread. A material that is both superconducting at room temperature and stable at ordinary pressure would represent a paradigm shift in energy and technology, enabling lossless electricity grids, more affordable MRI machines, and faster, more efficient electronics.

OBJECTIVE OF THE STUDY:

This study explores the Progress and Challenges of Superconductivity at Room Temperature.

RESEARCH METHODOLOGY:

This study is purely based on secondary data sources such as articles, journals, research papers, books and websites.

Rapid materials discovery: high-pressure hydrides and why hydrogen-rich phases dominate recent progress

A defining trend of the last decade is the emergence of hydrogen-rich compounds (superhydrides) as the most promising route to very high critical temperatures. The chemistry reason is straightforward: light hydrogen atoms produce high-frequency phonons and can give very strong electron–phonon coupling, which in conventional (phonon-mediated) superconductivity often raises the superconducting critical temperature, Tc. That insight drove both theoretical searches and experimental high-pressure synthesis efforts, producing record Tc values in systems such as H3S (~203 K) and lanthanum superhydride LaH10 (~250 K) under megabar pressures. The LaH10 results — zero resistance, isotope effects, and magnetic suppression consistent with superconductivity — were landmark experimental confirmations of the theoretical strategy.

Experimentally, these materials are created inside diamond anvil cells at pressures of 100–300+ gigapascals. That environment stabilizes dense hydride stoichiometries and unusual crystal structures (often "clathrate-like" hydrogen cages around a heavier metal). Modern progress has come from a close feedback loop between first-principles crystal structure prediction, electron–phonon calculations, and experimental high-pressure synthesis and transport/magnetic measurements. Theoretical screens quickly identify candidate compositions and pressure ranges; experimentalists then attempt synthesis, often guided by laser heating and in-situ diffraction. Large teams combining ab-initio predictions with advanced diamond-anvil syntheses have accelerated discovery.

There are caveats. The megabar pressures required to stabilize many superhydrides are far above what engineering applications can tolerate. Producing and measuring a sample at 200 GPa is a tour de force of small-scale physics rather than a materials technology pathway. Also, high-pressure synthesis sometimes yields samples that are inhomogeneous, multiphase, or mixed with residual precursor materials, complicating interpretation of transport and magnetic data. Reproducibility across labs is uneven when sample preparation and pressure-temperature histories are hard to fully replicate. Those are practical but important limitations to "discovery" even when the physics principle is sound.

Finally, the materials frontier is branching beyond pure hydrides. Hybrid strategies—embedding hydrogen-rich units into clathrate cages, chemically precompressing structures with light elements (B, C), or searching for ambient-pressure analogs—are active research vectors. Computational design is pushing the search space toward systems predicted to retain high Tc at lower pressures; experimental demonstrations lag but are gaining traction. The combination of predictive theory, faster high-pressure synthesis, and improved in situ characterization tools explains why hydrides dominated the high-Tc headlines and why materials discovery remains a fast, collaborative cycle.

Measurement standards, reproducibility, and the credibility problem after high-profile controversies

Progress in superconductivity depends critically on convincing, reproducible measurements: zero resistance, magnetic flux exclusion (Meissner effect), and consistent behavior versus magnetic field and isotopic substitution. But the field suffered a credibility setback from several high-profile, contested claims. These include the 2020 carbonaceous sulfur hydride report of superconductivity at ~288 K under extreme pressure and subsequent scrutiny and investigations that raised questions about data handling and reproducibility. Later community investigations and journal actions highlighted the importance of rigorous standards, full data sharing, and independent replication. Those events made clear that extraordinary claims require a high bar of independent confirmation.

The measurement challenge at megabar pressures is technical and multifaceted. Four-probe resistance measurements on micron-scale samples squeezed between diamond culets are hard: contact geometry, microcracking, current paths, and unrecognized short circuits can masquerade as low resistance. Magnetic measurements (e.g., SQUID) are difficult because the sample volume is vanishingly small relative to background signals, and diamond anvil cell materials contribute diamagnetic or paramagnetic background that must be subtracted carefully. Optical signatures and spectroscopic probes help but are not standalone confirmation. The field has therefore emphasized cross-checking with multiple, independent probes (resistivity, magnetization, heat capacity, isotope effect), and publishing complete raw data, instrument settings, and calibration procedures.

Community response to the controversies has been constructive: several multi-lab replication campaigns, open data requests, and meta-investigations by journals and institutes have improved transparency. That process also revealed systemic weaknesses: small sample sizes, limited access to specialized pressure apparatus, and variable standardization of protocols across groups. For the field to move from "interesting discoveries” to reliable materials science, standardized measurement protocols (e.g., agreed checks for contact resistance, magnetization baselines, and pressure calibrations) and routine independent replications should become the norm.

In short, measurement credibility is now as central to progress as materials design. The community’s intensified focus on rigorous, multi-probe verification and reproducibility is a major non-technical advance that will influence which reported high-Tc materials are accepted and pursued.

Mechanisms: when conventional electron–phonon theory works and where unconventional physics may matter

Understanding why a material superconducts at high temperature is crucial for rational design. For many hydrides, conventional electron–phonon mediated superconductivity (the Migdal–Eliashberg framework) appears to explain the high Tc: light hydrogen produces very high phonon frequencies and strong electron–phonon coupling constants, and these inputs feed into Eliashberg calculations that predict high transition temperatures consistent with experiments like H3S and LaH10. That agreement boosted confidence that conventional mechanisms can reach extremely high Tc if the lattice and electronic structure cooperate.

Yet not all high-Tc claims fit neatly into the conventional picture. Correlated electron systems (cuprates, iron pnictides) show superconductivity tied to electronic interactions, spin fluctuations, and proximity to competing orders — phenomena beyond simple electron–phonon coupling. Distinguishing between phonon-driven and unconventional mechanisms requires several cross checks: isotope effect magnitude and sign, tunneling or spectroscopic fingerprints of the pairing glue, and theoretical checks on whether Migdal’s approximation (small electron mass relative to phonons) holds. In many hydrides the isotope effect (hydrogen vs deuterium substitutions) has provided key evidence supporting phonon mediation, but subtleties remain when anharmonicity, quantum zero-point motion, and strong coupling push standard approximations to their limits.

Theoretical work is extending conventional frameworks to include anharmonic phonons, quantum ionic motion, and nonadiabatic effects that become important for the lightest atoms. These refinements change quantitative Tc predictions and sometimes the qualitative picture of which phonon modes dominate pairing. There are also proposals for hybrid mechanisms where phonons cooperate with electronic fluctuations, potentially opening new routes to high Tc without requiring extreme pressures. But such theories need experimental tests — spectroscopic probes, isotope studies, and high-resolution structure determinations — to be validated.

In practice, mechanism studies guide materials search: if electron–phonon pairing really can produce room-temperature Tc under accessible conditions, one strategy is to engineer phonon spectra and electronic densities of states to maximize pairing while avoiding lattice instabilities. If unconventional mechanisms dominate, different design rules (e.g., tuning correlation strength or magnetic interactions) would be needed.

Current evidence places many superhydrides in the “conventional, phonon-driven” camp, but the boundary is active research territory where theory and experiment still need to converge.

Pressure: the double-edged sword of megabar stabilization and the quest for ambient conditions

High static pressures in diamond anvil cells have been essential to create phases that do not exist at ambient conditions. Those pressures compress electronic states and force hydrogen into dense frameworks that support strong electron–phonon coupling. This is why record-high Tcs have been achieved only under megabar pressures: the same structural motifs are unstable at low pressure. But pressure is also the main barrier to applications. Devices and magnets require sizable volumes of material at ambient pressure and realistic mechanical robustness; a brittle, micrometer-scale sample in a diamond cell is not useful for power transmission or MRI magnets.

Two broad strategies are pursued to remove the pressure barrier. One is chemical precompression: design compounds where heavier elements or covalent frameworks mimic the electronic and structural effects of external pressure, allowing hydrogen-rich motifs to persist at much lower pressures (or even ambient). Proposed architectures include hydride units locked into boron-carbon clathrates or other scaffolds predicted to stabilize high-frequency vibrations without extreme compression. Computational designers have proposed candidate compositions that, in principle, reduce the required pressure; experimental realization remains difficult but not impossible.

A second approach is metastability: synthesize a high-pressure phase and then quench it to ambient pressure in a metastable state. Metastable retention of high-pressure phases is common in chemistry, but maintaining the delicate hydrogen networks that enable high Tc is particularly challenging because hydrogen readily diffuses or the structure relaxes when pressure is released. Controlled quenching, chemical substitution to “lock” the structure, or epitaxial thin-film stabilization are being explored. Each has technical hurdles in synthesis, characterization, and scale.

There is a more pragmatic angle: applications that can accept pressure or small device sizes (research magnets, micro-electronic components, or sensors) might exploit high-pressure superconductors even if they never become bulk power technologies. Realistically, however, the community still treats ambient-pressure stabilization as the central materials engineering challenge for transformative, real-world impact.

Scaling, materials processing, and engineering hurdles for real devices

Even if an ambient-pressure, room-temperature superconductor is found, moving from a measured sample to usable wire, tape, or bulk components requires mastering materials processing. For conventional superconductors (NbTi, Nb_3Sn) decades of alloying, drawing, and heat treatment produced ductile, manufacturable conductors. High-Tc cuprates required entirely different processing—thin films and textured ceramics—to manage grain boundaries and current flow. The practical lesson is that superconductivity in a bulk sample is only the first step; engineering useful critical current density (Jc), mechanical strength, manufacturability, and thermal stability is a long development program.

Key engineering metrics differ by application: power transmission values prioritize high critical current at low magnetic field and low cost per ampere-meter; magnets require high Jc under intense fields and mechanical robustness; electronics need thin-film patternability and interface compatibility. Many high-Tc hydrides, even if ambient-stable, may be brittle, chemically reactive, or require specific microstructures that are hard to scale. Processing routes (sintering, tape casting, thin-film deposition) would have to be developed from scratch, and likely substantial alloying or composite strategies would be needed to make conductors usable.

Another non-trivial issue is heat management. Superconducting devices still need thermal stabilization and quench protection; a room-temperature superconductor would relax cryogenics but not eliminate the need for thermal and electromagnetic engineering. Moreover, forming good contacts, managing flux pinning (to prevent flux motion and dissipation), and ensuring long-term chemical stability in operating environments are all materials engineering tasks that typically take years of industrial development. The pathway from discovery to infrastructure transformation will therefore require sustained multidisciplinary effort beyond condensed matter labs.

The near-term outlook: cautious optimism, focused priorities, and realistic timelines for impact

The field sits at a productive intersection: theoretical tools and high-pressure techniques produced unprecedented Tc records, and the community has learned hard lessons about reproducibility and standards. Recent theoretical work has even revisited hard limits on conventional superconductivity, suggesting that ambient-temperature conventional superconductors may be feasible within fundamental bounds — though those studies are sensitive to assumptions about coupling strengths and lattice stability. This combination of promising theory plus experimental capability justifies cautious optimism: room-temperature superconductivity is not logically impossible, but turning that physics into a stable, ambient-pressure, manufacturable material is the central technical problem.

Research priorities that follow are clear: (1) materials design targeted at ambient-pressure stability (chemical precompression, clathrate strategies); (2) robust, multi-probe measurement standards and multi-lab replications; (3) studies of mechanism that refine predictive theories (including anharmonic and quantum ionic effects); and (4) early engineering studies of processability and critical current in promising candidates. Success will require combining high-throughput computation, advanced synthesis, and open, reproducible measurement. Taken together, the last decade showed that dramatic Tc increases are achievable under special conditions and that the community can pivot quickly to assess, reproduce, and refine claims. The remaining challenge is no longer simply “can we reach room temperature?” — theoretical and experimental evidence suggests that might be reachable — but “can we do so in a material that is stable, scalable, and usable at ambient pressure?” Answering that question will determine whether room-temperature superconductivity moves from headline breakthroughs to technologies that reshape energy, transportation, and computing.

CONCLUSION:

The pursuit of room-temperature superconductivity has advanced rapidly, especially with the discovery of hydrogen-rich compounds capable of superconducting at temperatures approaching or surpassing ambient conditions under extreme pressures. These achievements validate long-standing theoretical predictions that electron–phonon coupling in light-element systems can support extraordinarily high critical temperatures. However, the reliance on megabar pressures highlights the gulf between laboratory breakthroughs and practical technologies. Equally important are the lessons learned from issues of reproducibility and data integrity, which underscore the necessity of rigorous verification and collaborative, transparent research practices. Looking forward, the central challenge is to discover or engineer superconductors that retain their properties at ambient pressure and in scalable forms. Strategies such as chemical precompression, metastable phase stabilization, and hybrid material design offer promising paths. Success in these directions would redefine the boundaries of energy technology, medical imaging, transportation, and quantum devices. While timelines remain uncertain, the combination of advanced computational methods, high-pressure experimentation, and global collaboration provides cautious optimism. The quest for room-temperature, ambient-pressure superconductivity is not only a milestone for physics but also a transformative opportunity for modern technology.

REFERENCES

1. Drozdov, A. P., Eremets, M. I., Troyan, I. A., Ksenofontov, V., & Shylin, S. I. (2015). Conventional superconductivity at 203 kelvin at high pressures in the sulfur hydride system. *Nature*, *525*(7567), 73–76.
2. Drozdov, A. P., Kong, P. P., Minkov, V. S., Besedin, S. P., Kuzovnikov, M. A., Mozaffari, S., … Hemley, R. J. (2019). Superconductivity at 250 K in lanthanum hydride under high pressures. *Nature*, *569*(7757), 528–531.
3. Eremets, M. I., & Troyan, I. A. (2011). Conductive dense hydrogen. *Nature Materials, 10*(12), 927–931.
4. Pickard, C. J., & Needs, R. J. (2011). Ab initio random structure searching: hydrogen, hydrocarbons, and high-Tc superconductivity. *Journal of Physics: Condensed Matter, 23*(5), 053201.
5. Somayazulu, M., Ahart, M., Mishra, A. K., Geballe, Z. M., Baldini, M., Meng, Y., … Hemley, R. J. (2019). Evidence for superconductivity above 260 K in lanthanum superhydride at megabar pressures. *Physical Review Letters, 122*(2), 027001.