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Using Silicon in Lithium-Ion Batteries

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The Defense Systems Information Analysis Center (DSIAC) is a DoDIAC sponsored by DTIC to provide expertise in 10 technical focus areas: weapons systems; survivability and vulnerability; reliability, maintainability, quality, supportability, and interoperability (RMQSI); advanced materials; military sensing; autonomous systems; energetics; directed energy; non-lethal weapons; and command, control, communications, computers, intelligence, surveillance, and reconnaissance (C4ISR). DSIAC is operated by SURVICE Engineering Company under contract FA8075-21-D-0001.

TI Research

A chief service of the DoDIAC is free technical inquiry (TI) research limited to four research hours per inquiry. This TI response report summarizes the research findings of one such inquiry. Given the limited duration of the research effort, this report is not intended to be a deep, comprehensive analysis but rather a curated compilation of relevant information to give the reader/inquirer a "head start" or direction for continued research.

Abstract

The Defense Systems Information Analysis Center was asked to identify organizations performing research in using amorphous silicon oxycarbide (SiOC) to replace conventional graphite in lithium-ion batteries (LIBs) and publications on the topic. Graphite is commonly used as a material for anodes in LIBs because of its fast-charging properties, high specific energy densities, and long life cycles. However, concerns about graphite's rate performance and low conductivity have spurred research into using other materials in LIBs, including Si and SiOC. This report lists organizations performing research in this area and summarizes their findings.

Contents

1.0 TI Request

1.1 Inquiry

What current research is available that describes using amorphous silicon oxycarbide (SiOC) to replace conventional graphite in lithium-ion batteries (LIBs)?

1.2 Description

The inquirer is interested in reports, publications, and subject matter experts (SMEs) related to SiOC in LIBs. Also requested was a list of U.S. Department of Defense (DoD) and U.S. government organizations performing research in this area.

2.0 TI Response

The Defense Systems Information Analysis Center (DSIAC) was asked to identify current research on using amorphous SiOC to replace conventional graphite in LIBs. DSIAC staff searched open-source documents and the Defense Technical Information Center's R&E Gateway and consulted with SMEs in the field of battery research, particularly LIBs. A list of organizations, points of contact (POCs), and relevant publications are included in this report, with summaries of the research when available.

2.1 Background

LIBs are "a type of rechargeable battery that stores and discharges energy by the motion or movement of lithium ions between two electrodes…called the cathode and anode through an electrolyte" [1]. The negatively charged anode "discharges lithium ions into the electrolyte" and conveys them to the positively charged cathode, where they are absorbed. Figure 1 shows the process of how a LIB works. LIBs tend to be energy dense, durable, and eco-friendly and are used in mobile phones, digital cameras, laptops, solar cells, and electric vehicles (EVs). Using LIBs in EVs is a newer concept, so research is ongoing in that area.

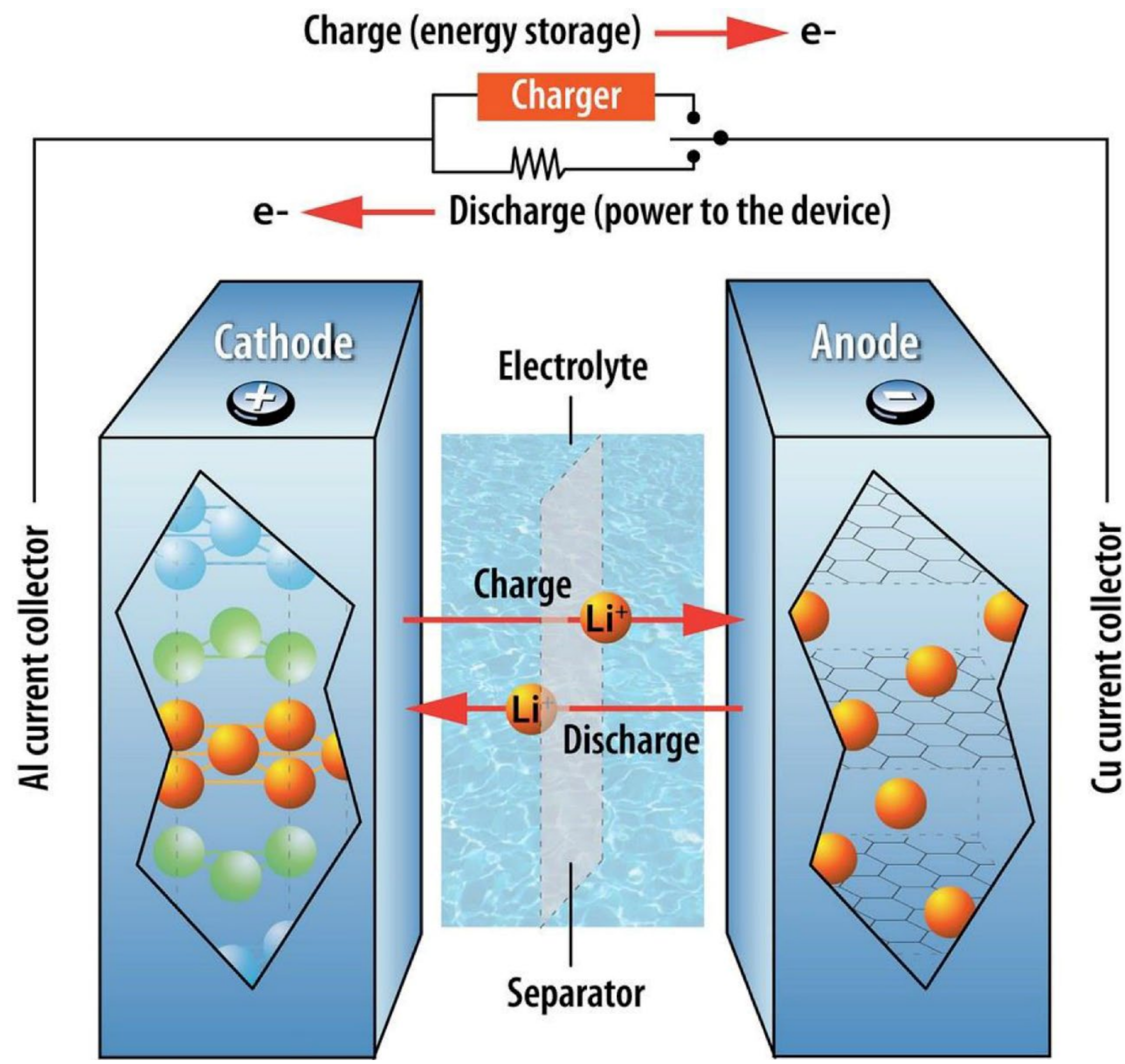

Figure 1. A Schematic Diagram of a LIB *(Source: Nzereogu et al. [1]).*

Widely used as a material for anodes in LIBs, graphite typically prevents the "anode material's shape, size, and structure from changing during the charge-discharge process" [1]. Graphite anode materials are also known for having fast charging properties, high specific energy densities, and long life cycles [2]. Typically, the "low electrochemical potential, low cost, low toxicity, and high abundance make it ideally suited" for use [3].

Graphite tends to have a "low capacity and unstable cycle performance," so alternatives are needed [4]. When it comes to using graphite in rechargeable LIBs, previous studies have shown it exhibits "low discharge potential, low Li^+ diffusion rate, and easy precipitation of lithium dendrites in practical applications" [5]. To address these disadvantages, researchers have explored modifying graphite anode technologies and using alternative materials.

Research on using Si-based materials, including SiOC, to replace the use of graphite in LIBs is an area being explored. SiOC is “an amorphous glass-like ceramic” with a porous nature, which, when combined with the “evenly distributed free carbon phase in SiOC, contribute[s] to the improvement of electrical conductivity and lithium-ion reversibility” [4]. SiOC tends to have high specific capacity and better structural stability than graphite when used in anodes for LIBs. Low conductivity and “poor rate performance” are concerns being researched for improvement [6]. There is conflicting evidence on the pros and cons of SiOC for use in LIB anodes, which has fueled more research in the area.

This report identifies U.S.-based research, organizations, and POCs doing work in this area, which will be listed alphabetically. Summaries of the research being done are also included.

2.2 Organizations

Organizations are grouped in three categories: (1) the DoD and U.S. government, (2) academia, and (3) industry. This is not an exhaustive list but aims to provide an overview of current research being done in the past five years. A few studies from outside the five-year mark are included due to their relevancy.

2.2.1 The DoD and U.S. Government

Research on SiOC in LIBs has been sporadic and shown varying results. Summaries of research on the use of SiOC in LIBs are included for each organization listed as well as organizations doing general research in LIBs and using Si materials other than SiOC. These organizations are listed alphabetically in the following paragraphs.

Argonne National Laboratory

Researchers with Argonne National Laboratory demonstrated “the increased capability of a potential new, higher-capacity anode material” for use in LIBs [7]. Si and phosphorous were explored due to both having a theoretical energy capacity 10× greater than graphite, “meaning they could surpass the energy capacity requirements for LIBs.”

Si was found to have the following two main concerns [7]:

1. High-volume expansion during charging, likely leading to the anode material breaking apart and a loss of energy capacity.

2. An initial Coulombic efficiency ratio of less than 80%. Practical use requires the ratio to be above 90%, meaning not much lithium is lost during the battery's initial charging and discharging cycle.

The research led the team to explore black phosphorous as another option, as it was shown to be a stable composite with high conductivity; however, further research is ongoing.

U.S. Department of Energy (DoE)

The DoE is researching multiple aspects of using Si in LIBs. The Federal Consortium for Advanced Batteries (FCAB) developed the "National Blueprint for Lithium Batteries 2012 – 2030," which identified five goals and key actions "to guide federal agency collaboration" [8, 9]. While the blueprint does not specifically mention Si, the first goal mentions "discover[ing] alternatives for critical materials for commercial and defense applications" for LIBs [9].

Approximately $600M was appropriated annually for fiscal years 2022–2026 as part of the Battery Materials Processing Grants Program, which provides grants for "battery materials processing to ensure the United States has a viable battery materials processing industry" [10]. A notice of intent was released on January 10, 2025, with a focus "on facilities that support the energy independence of the United States through circulatory and secure sourcing," to include production of materials for anodes [11]. Identifying how SiOC can be used in anodes falls under this third round of projects.

DoE's Vehicle Technologies Office is exploring new battery materials for use in transportation by "investigat[ing] new and promising materials for future battery chemistries" by looking at Li-ion anodes with a "higher capacity than traditional carbon based electrodes" [12]. Researchers in this group are working with Lawrence Berkely National Laboratory and the Massachusetts Institute of Technology to "run the Materials Project," a "search engine interface" that can sort over 20,000 different materials. The Materials Project also includes a LIB Explorer, which researchers use to identify "materials that satisfy critical criteria for lithium batteries." The Vehicle Technologies Office also developed the Battery Performance and Cost Model at Argonne National Laboratory, which is designed for policymakers and researchers to estimate costs for Li-ion battery scenarios [13].

Department of the Navy Operational Energy (DON-OE)

The DON-OE is partnered with multiple organizations on the Jumpstart for Advanced Battery Standardization (JABS) project "to accelerate the adoption of commercially-proven electric vehicle (EV) battery technologies by prototyping battery systems based on standardized modules that leverage state-of-the-art technology and manufacturing capabilities" [14]. While not entirely focused on SiOC use in LIBs, JABS certainly has the resources to explore this research area.

National Renewable Energy Lab (NREL)

Researchers with NREL are exploring LIB technologies for EVs and have created the Lithium-Ion Battery Resource Assessment Model (LIBRA) to aid in their research [15]. LIBRA analyzes the supply chain and economic viability of LIB manufacturing, reuse, and recycling of LIBs. NREL's chief energy storage engineer has focused his research on LIBs for EVs to include advancements using Si in LIB anodes [16]. Using Si-graphene composite anodes has "significantly improved the stability of [the] anode at liquid interface," improving the life cycle. Si anodes can also "contribute to low-grade fuels" and "has five to eight times the capacity of graphite anodes" but presents its own challenges, including decreased calendar life.

Using Si anodes in LIBs is appealing due to Si having "an eight-times-higher theoretical specific capacity for lithium-ion storage" compared to graphite, "allowing more energy per unit mass" [16]. Si's capacity cannot exceed more than 3–5× the capacity of graphite without impacting the "structural integrity of anode particles." They also tend to "expand and contract during charge and discharge cycles…caus[ing] the anode to crack and lose its electrical conductivity" which leads to decreased lifetimes and performance. NREL's recent research has tried to overcome some of these limitations by "designing nanostructured silicon materials, coating silicon with carbon or other materials to improve stability and incorporating silicon into composite anodes with other materials" [16].

Sandia National Laboratory

Sandia National Laboratory offers research opportunities for Harry S. Truman Fellows in National Security Science and Engineering. A fellowship was offered in 2023 to "improve performance in rechargeable lithium metal batteries" [17]. The research is exploring "techniques to determine how long a lithium-ion battery with a silicon anode maintains a charge while sitting idle." The fellow previously developed a voltage-hold protocol that is now the standard with the DoE's Vehicle Technologies Office Silicon Battery Projects, and the research is continuing in a project with the Department of Homeland Security to “improve performance and safety in rechargeable lithium metal batteries.”

2.2.2 Academia

The following academic institutions performing research on using Si in LIBs are listed alphabetically. A summary of research being done by each institution is also included.

Clemson University

A 2023 study, conducted by Clemson University researchers, created two new SiOC materials to improve battery performance—SiOC-I and SiOC-II—both for use as anode materials for LIBs [18]. These materials offer high stability and capacity and are fire resistant, making them safer than graphite. Researchers hope this will “advance solid-state batteries, potentially eliminating the need for the liquid organic solvent typically found in lithium-ion batteries.”

Another study from 2023 investigated SiOC materials for anodes in LIBs, specifically crystalline Si-based anodes: “The amorphous nature of these materials and their micro–mesoporous structure make them capable of accommodating large strains when charged or discharged” [19]. To address typical challenges with using SiOC anodes (low electrical conductivity, low Coulombic efficiencies, large hysteresis, and high first-cycle losses), researchers used “nanoparticles, prelithiation, and thin-film geometries.”

Finally, a third study explored “efficient SiOC-based anode materials that [can] mitigate” limitations of SiOC [20]. The electrochemical performance was improved when mixed with graphene nanoplatelets while “high specific capacity…was achieved with the composite anode (25 wt% SiOC-II and 75% graphene nanoplatelet [GNP])” compared to monolithic SiOC-I, SiOC-II, or GNPs [20]. Cycling stability and high reversibility were achieved, making a SiOC-GNP composite “a promising anode material for LIBs.”

Kansas State University (KSU)

KSU researchers are exploring the use of SiOC fibers as supercapacitor electrodes [21]. They fabricated a “precursor-derived SiOC fibermat via one-step spinning from various compositions of siloxane oligomers followed by stabilization and pyrolysis,” which “reveal[ed] transformation from polymer to ceramic stages of the various SiOC ceramic fibers.” Embedding a free carbon phase in the “amorphous [SiOC] structure” improves conductivity and gives a site for ion storage, “contribut[ing] to high efficiency.”

Another research project from KSU's Mechanical and Nuclear Engineering Department, albeit a bit dated (2016), studied a "self-standing anode material consisting of molecular precursor-derived silicon oxycarbide glass particles embedded in a chemically-modified reduced graphene oxide matrix" [22]. The amorphous SiOC particles "cycle lithium-ions with high Coulombic efficiency." Researchers reduced the total electrode weight by eliminating inactive ingredients, aiming to develop "efficient lightweight batteries."

Montana State University (MSU)

MSU was awarded $3.5M for advanced battery research in 2021 "as part of a $10 million effort involving universities, national labs, and industry partners" [23]. MSU is working on the U.S. Army Research Laboratory (ARL) effort, led by the University of Maryland (UMD), to research batteries "that can hold more power and charge faster while also being safer and more resilient to extreme environments." MSU is using past research on ceramic materials for fuel cells and applying it to battery research for the project. They are focusing on "developing and testing lithium-ion batteries that use a specialized ceramic material in place of the plastic membrane and liquid electrolyte that are prone to damage and fire." Researchers are using the "freeze-casting" method that MSU developed in their work with the National Aeronautics and Space Administration and "since refined over years of fuel cell research at MSU." The stability of the new ceramics and "effects of impurities on their performance" is part of MSU's task in the interdisciplinary effort. They plan to observe "how the battery material changes and correlate that with battery performance." Additionally, the chemistry and biochemistry department is exploring "graphite- and silicon-based materials for the electrodes that release and absorb energy during battery operation." Testing equipment to analyze performance of the new batteries is also part of the effort.

MSU has patent-pending research for a Si-anode technology to "achieve a…thick solid electrolyte interphase (SEI) [protective] layer on Si-based lithium-ion cells" [24]. This can be used for LIB "cycling protocols to provide a rapid formation of a sustainable SEI layer." This research helps LIBs achieve optimal cyclability and maximum capacity, improving cyclability by 88% and capacity by five-fold, compared to traditional anode materials.

University of Illinois Urbana-Champaign

A 2024 study describes "the electrodeposition of a Si-dominant active material (EDEP-Si) onto three-dimensional-structured nickel scaffolds" and compares the "electrochemical properties, elemental composition, atomistic Si coordination, and molecular structure of EDEP-Si with highpurity amorphous Si grown via static chemical vapor deposition" [25]. Researchers observed that "ultrapure Si is not necessary for high electrochemical access to reversible charge storage," but limiting impurities can improve energy density and first cycle efficiency of LIB anodes.

UMD

UMD hosts the Center for Research in Extreme Batteries (CREB), which does the following [26]:

> aims to foster and accelerate collaborative research in advanced battery materials and technologies and characterization techniques. CREB's focus is on batteries for extreme performance, environments, and applications, such as those that may be used for defense, space, or biomedical applications.

CREB partnerships with the DoD and a variety of institutions are summarized or described throughout the report as related to Si battery research. CREB partners include the following [26]:

1. ARL
2. Argonne National Laboratory
3. Bren-Tronics, Inc.
4. Brookhaven National Laboratory (BNL)
5. UK Defense S&T Laboratory
6. Forge Nano
7. Graphenix Development, Inc. (GDI)
8. Ion Storage Systems
9. University of Dayton Research Institute
10. National Institute of Standards and Technology
11. New York Battery & Energy Storage Technology (NY BEST) Consortium
12. Saft America
13. Stony Brook University (SBU)
14. UMD

Multiple research projects are ongoing among CREB partners, including a $9M cooperative agreement from the DoD in 2022, led by CREB members, to advance transformational army batteries [27]. UMD received $8.55M, with the remaining being split between BNL and Argonne National Laboratories. A U.S. Army Combat Capabilities Development Command (DEVCOM) ARL research thrust of Si anodes is being led by CREB members, GDI, MSU, SBU, BNL, and NY BEST.

University of Texas at Dallas (UT Dallas)

A three-year, $30M project was awarded to UT Dallas to establish an energy storage systems campus to “accelerate transition and scaling of next generation batteries, while reducing dependence on scarce critical materials” [28]. The award is part of the DoD’s Scaling Capacity and Accelerating Local Enterprises initiative. Its objectives include (1) optimizing Li-ion battery performance, (2) accelerating development and production of next-gen batteries, and (3) ensuring availability of raw materials needed for next-gen batteries.

The project lead is also the director of the Batteries and Energy to Advance Commercialization and National Security Center, whose goals are as follows [29]:

1. Optimizing existing battery systems, including integrating robotics and automation into manufacturing.
2. Fostering the development of new battery chemistries that reduce the use of scarce raw materials.
3. Identifying and tracking supply chain challenges for critical minerals like lithium that are needed in energy storage systems.
4. Developing the workforce needed for energy storage system development and manufacturing.

2.2.3 Industry

The following companies are listed alphabetically and were found to have current research on using Si or SiOC in LIBs related to DoD use.

Amprius

Amprius has a patented Si-anode technology to improve LIBs for use in aviation and electric vehicles [30]. The technology has increased the endurance, run time, and range of their LIBs and has been used in battery packs for Soldier wearables to extend mission time. In February 2025, Amprius received a $15M purchase order for their SiOC cells from “a leading UAS manufacturer” [31]. This follows a prior $20M contract for light electric vehicle applications from September 2024, with both DoD contracts remaining anonymous.

NanoGraf Corporation

NanoGraf has received multiple orders from the DoD for their Si battery technology. The first was a $1.56M partnership with the DoD to develop a Si battery for portable electronic gear using a Si anode as opposed to the traditional graphite [32]. NanoGraf developed the M38 18650 Si battery for the U.S. military, used mainly for handheld radios.

On June 10, 2024, "NanoGraf credited the Defense Department…with supporting the development of its new 800 watt-hour per liter (Wh/L) silicon battery" [32]. The new battery "provides compelling benefits for virtually any application — from consumer electronics to electric vehicle batteries to the batteries that power the equipment soldiers use during operations." Another 2024 order from the DoD was announced in July 2024 for stronger, lighter, longer-lasting LIBs [33]. According to NanoGraf, the "proprietary silicon anode technology will allow U.S. soldiers to continue using their devices for up to 15% longer compared to what they use today" [33].

Finally, NanoGraf received a $60M grant from the DoE's Office of Manufacturing and Energy Supply Chains "under the Bipartisan Infrastructure Law (BIL) fund supporting new and expanded commercial-scale domestic battery manufacturing projects" [34]. Funds are being used to retrofit a manufacturing facility in Flint, MI, to produce proprietary Si-anode battery material. This will "create one of the world's largest silicon anode facilities, significantly advancing U.S. efforts to onshore the battery supply chain and enhancing the performance of domestically made lithium-ion batteries."

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