

2D QUANTUM METAMATERIALS

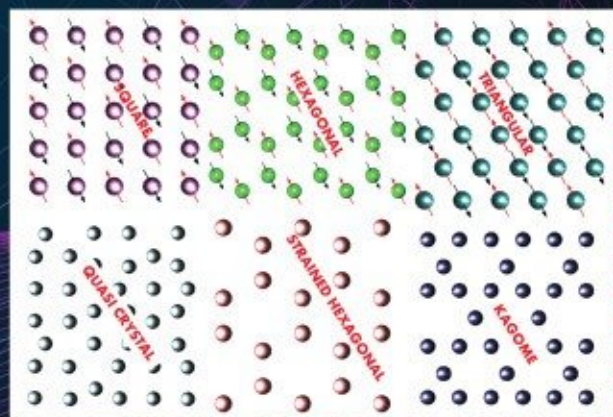
2018 NIST WORKSHOP

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Section I — General outcome and conclusions

1. Introduction and objective

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1.1. *Genesis, mission, and objectives of the workshop*

The idea of a Workshop on 2D Quantum Metamaterials began in 2015 when John Randall and Wiley Kirk were considering methods of utilizing scanning tunneling microscopes for atomically precise lithography and in particular for applications involving atomically precise semiconductor doping. The merits of holding a workshop became more consequential after a few program managers indicated a workshop would help with long-range planning and the development of program objectives. By late 2016, a concerted effort to formalize an organizing committee was undertaken. The individuals who agreed to be members of the organizing committee were — Richard M. Silver and Neil Zimmerman at the National Institute for Standards and Technology; Shashank Misra, Clark Highstrete, and Ezra Busmann at Sandia National Laboratories; John N. Randall, James Owen, and Joshua Ballard at Zyvex Labs, LLC; and Wiley P. Kirk at University of Texas at Arlington and 3D Epitaxial Technologies, LLC.

The mission of the workshop as outlined by the organizing committee was to explore commonalities between fabrication, theoretical prediction, and alternative approaches to tunable quantum materials as currently realized by several approaches. Specifically, the different approaches included semiconductors doped with atomic precision, optical lattices and cold-atoms, trapped ions, superconducting circuits, approaches using entities such as quantum dots, and finally approaches based on photonic systems.

The objective of the workshop was to address and answer as best possible the following set of questions:

- (i) What is meant by a 2D quantum metamaterial from both theoretical and empirical perspectives? What might result from investigating such structures?
- (ii) Can placement of dopant atoms with atomic-scale precision in semiconductors lead to analog quantum simulations (AQS)?
- (iii) What other approaches lead to AQS? How do the various approaches compare?
- (iv) To what extent can the Fermi–Hubbard model be implemented and what role might it have in expanding the horizon of physics in strongly correlated systems?
- (v) Of the various technologies that can be used to make 2D quantum metamaterials, what are the advantages and disadvantages of each?

1.2. Logistics, venue, attendance statistics

The workshop was held over a two-day period, April 25–26, 2018, as a mix of invited speakers and breakout sessions. This arrangement provided overviews of the most recent experimental and theoretical developments in each area of approach along with summarization and recommendation reports from the breakout session leaders. The workshop was held at the National Institute for Standards and Technology in Gaithersburg, Maryland, USA. Of the 87 registrants, 32 professionals were from government laboratories, agencies, and industry; 55 were professors, postdocs, and students from academia, and 5 were international participants.

1.3. Organization of presentations, breakout sessions, and sponsors

Three plenary presentations anchored the workshop's agenda:

1. Designing quantum materials in silicon, atom by atom
Shashank Misra
Sandia National Laboratories
2. A new toolbox for quantum many-body physics
Gabe Aepli
Paul Scherrer Institute, Switzerland
3. The disordered Hubbard model: from Si:P to the high-temperature superconductors
Subir Sachdev
Harvard University

Ten additional presentations determined the breadth and depth of the agenda:

1. Critical quantum chaos and room temperature effects in 1D arrays of P donors in silicon
Enrico Prati
Institute for Photonics and Nanotechnologies, Milan, Italy
2. Fabrication of atomic-precision dopant arrays in Si using STM-based hydrogen lithography
Jonathan Wyrick
National Institute of Standards and Technology
3. Cold Atoms — From simulation to discoveries
Cheng Chin
University of Chicago
4. Quantum Simulation and Lattices in Circuit QED
Alicia Kollar
Princeton University
5. Quantum simulations with a semiconductor quantum dot array
Sjaak van Diepen
Delft University of Technology

6. Tunable solid state 2D quantum materials
Ingmar Swart
Utrecht University
7. Ultracold matter for quantum simulations: achievements, challenges,
& opportunities
Kaden Hazzard
Rice University
8. Quantum simulation and quantum information with trapped ions
Norbert M. Linke
University of Maryland
9. Atom-based photonics, quantum plasmonics and many-body physics
Garnett W. Bryant
National Institute of Standards and Technology
10. Moiré is different: Bi-layer graphene as a meta material
Philip Phillips
University of Illinois at Urbana-Champaign

Breakout sessions were organized around four teams, each with a moderator and notetaker to record each team's discussions and recommendations. The following individuals served as moderators and notetakers respectively: Team 1: Joseph Lyding, University of Illinois at Urbana-Champaign (moderator), Angela Hight Walker, NIST (notetaker); Team 2: Neil Curson, University College London (moderator), Scott Schmucker, NIST (notetaker); Team 3: Irma Kuljanishvili, Saint Louis University (moderator), Igor Altfeder, Ohio State University (notetaker); Team 4: Albert Davydov, NIST (moderator), Curt Richter, NIST (notetaker). Each team was assigned the goal of producing a PowerPoint slide that captured their group's discussion and recommendations. On the last day, each team presented their team's outcome to all the registrants of the workshop. Along with general discussions, each team was asked to incorporate specific discussions on questions such as:

1. Are there general impediments to using an atomically precise dopant array for analog quantum simulations?
2. Are there particular advantages to the dopant array approach?
3. Are there particular disadvantages with the dopant array approach?
4. Are there particular lessons based on area of expertise, including other experimental realizations, that are useful for considering the dopant array approach?
5. Are there specific results from other experimental realizations (for instance, certain parameter values) that cannot be achieved by the dopant array approach?
6. Are there advantages or disadvantages of the various approaches when considering employment of manufacturing steps?
7. Finally, members of the breakout sessions were asked to consider the

degree to which an atomically precise dopant array is an attractive candidate for two-dimensional quantum materials, and in particular for executing analog quantum simulations as realized in models such as Fermi–Hubbard?

Sponsors

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