Journal of Applied Physics

EDITORIAL | APRIL 13 2021

Materials for quantum technologies: Computing, information, and sensing FREE

Special Collection: Materials for Quantum Technologies: Computing, Information, and Sensing

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J. Appl. Phys. 129, 140401 (2021)
https://doi.org/10.1063/5.0050140

Journal of Applied Physics EDITORIAL scitation.org/journal/jap

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Cite as: J. Appl. Phys. **129**, 140401 (2021); doi: 10.1063/5.0050140
Submitted: 12 March 2021 · Accepted: 17 March 2021 ·
Published Online: 13 April 2021

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Note: This paper is part of the special collection on Materials for Quantum Technologies: Computing, Information, and Sensing.

Quantum information sciences (QIS) including quantum computing, quantum information, and quantum sensing have become a major area of interest for both fundamental scientific research as well as industrial applications. Quantum computing enables completely new territories of computing and allows for exponential performance improvement, quantum information ensures secure communication even in the face of unlimited quantum computing power, and quantum sensors provide measurements of various quantities that are orders of magnitude more sensitive than classical sensors.[1] Major scientific funders and companies around the world have made significant investments in advancing QIS research and technology, and the promise of a quantum revolution is hard to overstate. D-wave company offers their hardware by selling their quantum annealing platform commercially,[2] while IBM, Google, Microsoft, AWS, Rigetti, and QuTech offer cloud-based quantum computing platforms.[3] Several players offer commercial quantum key distribution systems,[4] and telecom providers, banks, and governments have started to invest.[5] A few companies offer stand-alone quantum sensors such as quantum gravity meter and atomic clocks based on laser-cooled atoms,[6] while others are still developing the underlying technology for sensors such as quantum electromagnetic sensors,[7] or highly sensitive magnetic field sensors that could be leveraged to develop quantum microscopes in the future.[8] However, quantum technology is currently in the Noisy Intermediate Quantum Scale (NISQ) era,[9] and major challenges remain in this field. Quantum computing is hampered by relatively short qubit decoherence times. Quantum information and communication is limited by the difficulty in maintaining and measuring entangled pairs over long distances. Quantum sensing requires a delicate balance between coupling the sensor to the environment and maintaining the quantum state.

Addressing these challenges necessitates advancements in all areas of science and engineering but choosing the right material for the application is of fundamental importance. For example, qubits can be made from a variety of materials, including superconductors in Josephson junctions, nitrogen-vacancy centers in diamond, defects in silicon, semiconductor quantum dots, trapped ions and atoms in optical tweezers, and so on. Each platform has its own advantages and disadvantages, and similar material choices are necessary for other QIS applications. In addition to optimizing the growth and fabrication of existing materials for refining their properties, research into new materials is needed to continue to advance the field. The "Materials for Quantum Technologies: Computing, Information, and Sensing" Special Topic in *Journal of Applied Physics* discusses both the properties of established materials for quantum technologies and emerging materials.

A tutorial on the growth of strain-driven self-assembled III–V semiconductor quantum dots by molecular beam epitaxy is presented by Sautter and co-workers.[10] Strain is also an important component in understanding the performance of silicon quantum dot devices as discussed by Stein and Stewart.[11] Chen and co-workers show that carbon nanotubes can be converted to graphene nanoribbons and carbon nanocrystals with the application of a femtosecond laser.[12] Plasma-assisted molecular beam epitaxy can be used to grow low-loss titanium nitride for use in tunnel junctions and quantum circuits as discussed by Richardson *et al.*[13] Also, aluminum-based tunnel junctions are investigated by Kim and co-workers using density functional theory to understand how material parameters impact performance.[14]

Point defects and dopants can both be used as quantum emitters and qubits in solid state materials. Eu^{3+}:Y_2O_3 thin films can be grown on silicon using chemical vapor deposition for a wide range of Eu concentrations as it is discussed by Harada *et al.*[15] Pak and co-workers show that ytterbium ions implanted into lithium niobate have strong emission and high quality factors.[16] Ishizu and co-workers demonstrate that a silicon oxide mask can be used to control the depth of nitrogen-vacancy centers created in diamond through nitrogen implantation.[17] Defect-bound exciton peaks are enhanced in WSe_2 on a rough substrate due to the Purcell effect, concentration of the electric field in rough features, and the strain-induced exciton funneling effect, as shown by Chaudhary *et al.*[18]

The creation of novel devices using new materials is crucial for the advancement of QIS. Kim *et al.* demonstrate that memristors fabricated from $SrFeO_x$ undergo a reversible topotactic phase change.[19] Bright light can be used to control a negative-feedback avalanche diode detector, as it is shown by Gras *et al.*[20] Delayed optical nutation in a photonic crystal fiber can be attributed to slow molecules, as discussed by Ocegueda and co-workers, which could be exploited for the observation of quantum coherent effects.[21] Debnath and Rubio discuss how multidimensional pump-probe analog spectroscopy can be used for investigating polariton characteristics and entanglement.[22] Finally, Jin and co-workers investigate the impact of channel parameters on the performance of continuous-variable quantum key distribution.[23]

The discovery of new materials, the refinement of existing materials, and the investigation of new devices are all crucial components to pushing the field of QIS forward. There is still significant work to be done both in understanding the fundamental physics of quantum systems as well as applying this understanding to the creation of new quantum devices. We hope the scientific community finds the Special Topic Collection on "Materials for Quantum Technologies: Computing, Information, and Sensing" to be of use in moving the field forward.

ACKNOWLEDGMENTS

The guest editors would like to thank all the authors who contributed work to the "Materials for Quantum Technologies: Computing, Information, and Sensing" Special Topic. This Special Topic was only successful due to the significant efforts of Journal Manager Brian Solis, Associate Editors Jaime Gomez-Rivas and Rachel Goldman, and the rest of the editorial team. S.L. acknowledges support from the U.S. National Science Foundation, Division of Materials Research under Award No. 1838504. S.K. acknowledges support from the Netherlands Organization for Scientific Research (NWO) under Grant No. 680-47-623.

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