Breakthrough in enhancement of hole mobility in strained germanium semiconductor leads to emergence of new class of quantum materials

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Semiconductor materials are the foundation of modern electronic, photonic, photovoltaic, thermoelectricand many other semiconductor devices, which are integral for computers, mobile phones, gadgets, homeappliances, cars and other equipment. More than 99% of all semiconductor devices are made of or on silicon (Si) wafers. Novel group IVsemiconductor epitaxial structures composed of Si, germanium (Ge), carbon or tin on Si wafers provide a natural route for continued improvement of properties of state-of-the-art Si devices with enhanced or emerging unique properties.

Mobility of free carriers in conduction (electrons) or valance (holes) bands, along with a reasonably large energy band gap, is one of the most important quality measures of any semiconductor material, determining its suitability for applications in a large variety of classical electronic, optoelectronic and sensor devices, as well as for novel applications in emerging quantum devices. Higher mobility enables faster operation of a device at lower power consumption and thus leading to reduced Joule heat dissipation, which is essential to minimize for continues circuit scaling as well for increasing the speed of current electronic devices. This is even more important for those devices and electronics to operate at cryogenic temperatures, for example, to control distributed registers of quantum processors.[1] Also, carrier mobility is the critical quality of a semiconductor material for quantum devices, often playing a key role towards new discoveries.[2]

Germanium is a semiconductor material that has been used in the semiconductor industry since the invention of the first transistor. It has some advantages over other semiconductors such as Si and various III-V compounds. In particular, if the mobility of holes in Ge can be enhanced through strain engineering, this could lead to the development of new types of quantum materials with unique properties. Quantum materials are materials that exhibit unique electronic and magnetic properties due to their quantum nature, and they are being studied for a wide range of applications including quantum computing, sensing, and energy storage. Semiconductor heterostructures on Si have a built-in strain that is induced by the mismatch of the crystal lattices of the composed materials. It is an essential parameter used for energy band structure engineering of a material.

Recently, a record-high mobility of holes, reaching of 4.3×10^{6} $\mathrm{cm^2V^{-1}s^{-1}}$ in an epitaxial strained Ge (s-Ge) semiconductor, grown on a standard Si(001) wafer was reported.[3] This significant increase of the mobility by over four times, compared to the state of the art, allows holes to outperform electrons in theg roup-IV semiconductor materials, for the first time. The demonstrated hole mobility in s-Ge is double that of the best mobility of electrons reported in state-of the art strained Si.[4] A similar situation has not been observed for any other semiconductor material system.

In addition to the record mobility, this material platform reveals a unique combination of properties, which are a very large and tuneable effective g*-factor, a low percolation density and a small effective mass. This long-sought combination of parameters in one material system is important for the research and development of low-temperature electronics with reduced Joule heating, and for quantum electronic circuits based on spin qubits, including devices for Majorana Fermions.[2]

This major breakthrough was achieved due to the development of state-of-the-art epitaxial growth technology culminating in superior monocrystalline quality of the s-Ge material system with a very low density of background impurities and other imperfections. This superior material system with the combination of unique properties will lead to new opportunities for innovative quantum device technologies and applications in quantum as well as in classical electronics, optoelectronics and sensors.

This achievement reduces the gap between the best hole mobility in gallium arsenide (GaAs) heterostructures grown on the same material substrate, which was just recently increased from 2.3×10^{6} $\mathrm{cm^2V^{-1}s^{-1}}$ to 5.8 $\mathrm{cm^2V^{-1}s^{-1}}$.[5,6] Unfortunately, III-V materials are complicated to process, expensive, not widely abundant in the Earth's crust compared to Si and Ge, do not exist in isotopically pure forms, and are not compatible with the state-of-the-art Si technologies for mass production. All other known semiconductors, including III-V, II-VI, perovskites, 2D materials, etc. show substantially lower hole mobility than in the s-Ge and GaAs heterostructures.

References

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