Keeping electronic devices cooler with nanoscale superlattice materials

By integrating nanoscale-thin superlattice materials with transistors and other electronic devices, scientists at Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore working on a project funded by the Department of Science and Technology have succeeded in recovering waste heat generated by their operation to make them more energy-efficient and extend their lifetimes.

Superlattices are made by periodic stacking of very thin alternating layers of two different materials that are either ideally lattice-matched. Novel electronic and photonic devices have been made possible by developing metal/semiconductor superlattices and engineering Schottky barrier heights of these artificially layered structures.

In this major research innovation, epitaxial single-crystalline TiN/(Al, Sc)N and (Hf, Zr)N/ScN metal/semiconductor superlattices were developed for the first time, and their Schottky barrier heights are measured with photoemission experiments. Epitaxy refers to material deposition where new crystalline layers are formed with a well-defined orientation with respect to a crystalline substrate.

Schottky barriers can control electrons flow at a metal/semiconductor junction and have rectifying characteristics suitable for use in diodes. Combinations of metal and semiconductors can change what is called the ‘Schottky barrier height’ which determines the energy efficiency of a device.

Thermoelectric materials should ideally exhibit high electrical conductivity, and low thermal conductivity and the present research relied on combining metals and semiconductors at nanoscale to achieve the desired properties.

Developing the metal/semiconductor metamaterials was challenging due to several fundamental and technological limitations, such as crystal structure mismatch and lattice-constant mismatch. But these were successfully addressed utilizing transition metal nitrides such as TiN, ZrN as metals and ScN, $Al_xSc_{1-x}N$ as semiconductors.

In a world full of electronic devices, the innovative metal/semiconductor superlattices are expected to be of great benefit in terms of energy savings, said the scientists from the Heteregenous Integration Research Group at the Jawaharlal Nehru Centre for Advanced Scientific Research, who have published the results of their work in Applied Physics Letters on 18 December and Journal of Materials Science, 2019 edition.

Integration of metals with semiconductors at the atomic-scale and development of metal/semiconductor superlattices were long sought after for energy conversion applications such as thermoelectricity, hot-electron plasmonics, optical metamaterials but were hampered by material compatibility challenges.

Semiconductors have helped develop solid-state lighting, photo-detectors, sensors, and high-speed power-electronic and optoelectronic devices. But the increasing demand for energy-efficient electronics and computing, secure information processing, energy security and imaging calls for more advanced materials such as Scandium Nitride (ScN) which can be epitaxially integrated with other metallic materials (such as TiN, ZrN, HfN, etc.) to deposit single-crystalline epitaxial metal/semiconductor multilayers and superlattices.

The newly developed lattice-matched superlattices are expected to lead novel energy conversion devices and address the increasing demand for alternative energy sources that are clean, affordable, and carbon-free. Presently, a significant portion of consumed energy (~ 60-70%) in almost all thermo-mechanical and electronic devices is wasted as heat.

The idea behind developing metal/semiconductor superlattices to cool transistors and electronic devices by recovering waste heat was developed thanks to the detailed fundamental understanding of the current and thermal transport mechanism in such materials.