Reinventing the Capacitor

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A capacitor is a device that stores and releases electrical charge. Its basic design consists of metal plates, separated by an insulating material. Capacitors are an essential part of all electronic circuits. They are thus fundamental to our modern technologies. In particular, capacitors are key components of field-effect transistors, which control the flow of charge in an electric circuit and are omnipresent in almost all modern microelectronic devices.

Transistors have been continuously miniaturised over the past few decades, in order to pack them more densely onto microchips. Recently, however, a fundamental physical limitation has stalled further progress.

The problem is that during their operation, transistors generate heat proportional to the consumed power. Although an individual transistor only produces a tiny amount of heat, in modern electronics transistors are packed together so densely, that the emitted heat approaches the limit of its possible removal. To overcome this issue, Professors Valerii Vinokur, Anna Razumnaya, and Igor Lukyanchuk of Terra Quantum are developing an ingenious solution, utilising an exciting device known as a 'negative capacitor.'

When electrical charge is applied to the plates of a regular capacitor, a voltage proportional to the applied charge builds up. The proportionality coefficient is called capacitance. In a negative capacitor, on the other hand, increasing the amount of charge applied to the plates induces a voltage of the opposite sign with respect to what would have appeared in the regular capacitor. This is thus referred to as negative voltage. Therefore, the capacitance is now negative. Combining negative capacitors into a larger circuit with regular capacitors allows the total capacitance of the whole circuit to be reduced, while keeping it positive.

The Terra Quantum team demonstrated that a negative capacitor can be created by placing a 'ferroelectric' material between the two plates instead of a standard insulator. A fundamental property of ferroelectric materials is that they remain electrically polarised in a specific direction even in the absence of an external electric field. This is similar to a ferromagnetic material, which remains magnetised even when there is no external magnetic field.

In a ferroelectric material, the constituent positive and negative ions are displaced with respect to each other, forming 'polarised ferroelectric molecules'. In this way, an internal electric field arises. The Terra Quantum team revealed that the lines along which the polarised molecules are aligned are remarkably similar to the flow lines in an incompressible liquid, such as water in a tank. These flow lines can form tornado-like formations called vortices, and intertwined knotted rolls called Hopfions, which look quite like balls of wool. Understanding the physics of Hopfions and vortices can help scientists to develop negative capacitors using ferroelectric materials.

Within a negative capacitor, the interior of the ferroelectric material splits into cells consisting of either Hopfions or vortices. When this material is a ferroelectric nanoparticle, these cells evolve into so-called 'polarisation domains'. Within a polarisation domain, all polarisation lines are aligned in the same direction. The Terra Quantum team showed that within a negative capacitor, a well-designed ferroelectric spacer splits precisely into two domains – each one having opposite electric polarisation to the other. Applying an electric charge to the capacitor's plates causes the wall separating these domains to move.

The polarisation within the material then redistributes itself, which induces an electric field opposite to that expected in a capacitor. The researchers found that as they increased the charge applied to their capacitor, the voltage decreased, and vice versa, which is characteristic of negative capacitance.

By incorporating a negative capacitor, a transistor can function at much lower applied voltage, resolving the problem of excessive heating. When implemented in a practical device, negative capacitance would allow transistors to be shrunk to the size of a strand of DNA. Such tiny capacitors could be packed together at unprecedented density, without producing excessive heat.

Harnessing negative capacitance would lead to a leap in the performance of microelectronic devices. This new generation of transistors containing negative capacitors would generate unprecedented advances in modern electronics – ranging from information processing technologies to quantum computing.