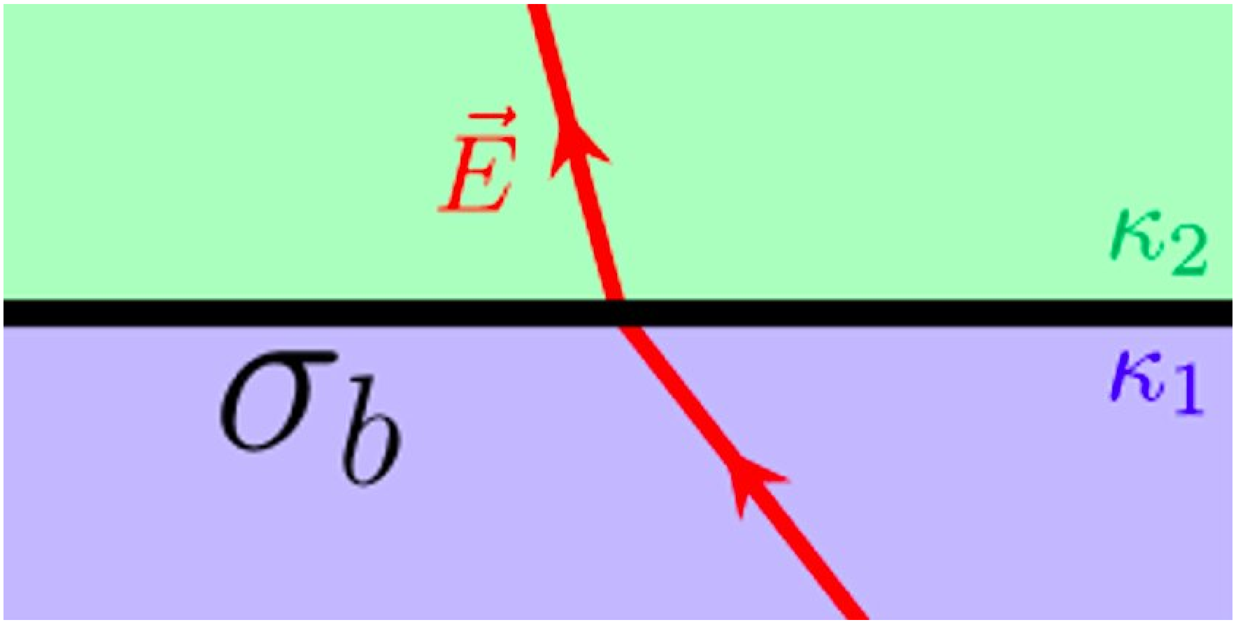
Bound-charge engineering: A new strategy to develop nanowire transistors

January 13 2021, by Ingrid Fadelli



A simplified version of Fig. 1.(a) from the researchers' paper. Caption: When an electric field ($\vec{E}$) is incident on the interface (black line) between two materials (blue and green regions) with distinct permittivity values (κ_1 and κ_2), a surface bound charge (σ_b) forms on that interface. Credit: Prentki et al.

In recent years, physicists and electronic engineers have been trying to identify materials that could be used to fabricate new types of electronic devices. One-dimensional (1-D) and two-dimensional (2-D) materials have been found to have particularly advantageous characteristics, particularly for the development of new generations of nanoelectronics (electronic components at the nano scale).

Such 1-D and 2-D materials, such as graphene, monolayer molybdenum disulfide, silicon nanowires and silicon nanosheets, could also play a crucial role within the semiconductor industry, as they could help to develop increasingly small transistors. Transistors are the basic building blocks of many modern electronic devices, which can store and control bits of binary information (i.e., zeroes and ones).

Despite their well-documented advantages, emerging low-dimensional materials can have a relatively small amount of so-called free charges compared to 3-D materials. In the context of electronic components, a free charge is an electron or hole (i.e., lack of an electron in an atomic lattice that acts as a positively charged electron) that is not tightly bound to the atomic lattice and is therefore able to move around freely throughout a material in response to external fields and applied voltages. Free charges have a number of important functions, one of which is their contribution to what is known as the screening effect.

In fact, free charges can redistribute themselves to create sharp electric potential profiles in both materials and devices, including in transistors. Therefore, the greater the number of free charges that material possesses, the sharper the resulting electric potential. This particular function is especially crucial for the development of tunnel field-effect transistors, which heavily rely on the quantum tunneling of electrons across junctions.

Researchers at McGill University and NanoAcademic Technologies have recently identified a strategy that could compensate for the lack of free charges observed in both 1-D and 2-D materials. In their paper, published in *Physical Review Letters*, they proposed the use of this strategy, which is based on the engineering of bound charges, to develop silicon nanowire transistors.

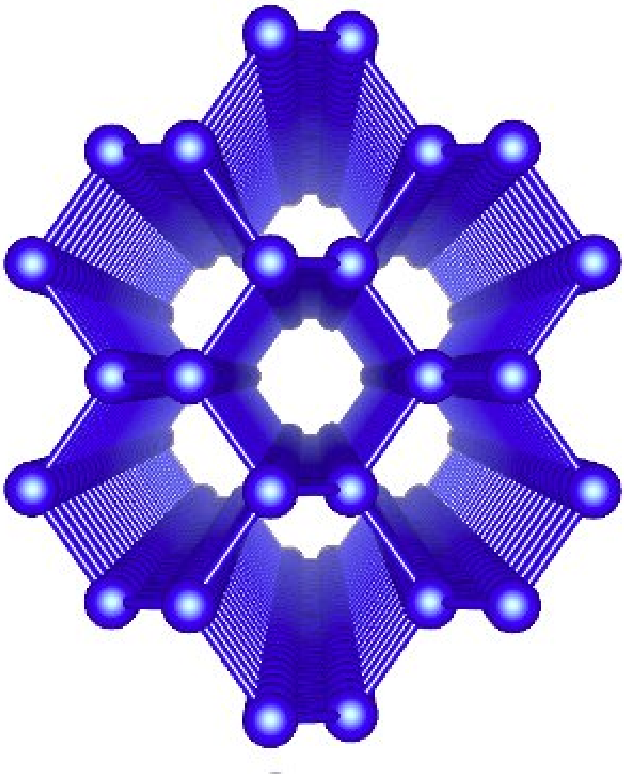


Image of one of the silicon nanowires that Prentki simulated in his work. Each sphere represents a silicon atom, and each bar represents an atomic bond between two neighboring silicon atoms. Credit: Prentki et al.

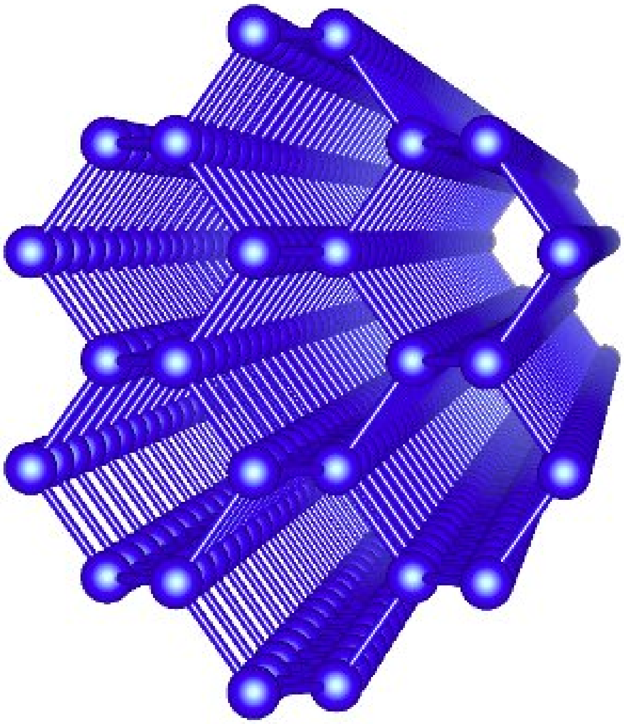
"The tunnel field-effect transistor has much lower power dissipations than conventional transistors, making it a promising candidate for low-power electronics," Raphaël Prentki, one of the researchers who carried out the study, told Phys.org. "For a tunnel field-effect transistor with sharper electric potential at the tunneling junction, the junction becomes more traversable, leading to improved device performance. We thus aimed to find a way to compensate for the lack of free charges in low-dimensional materials."

There are two types of charges in materials, namely free and bound charges. As their name suggests, free charges are loosely bound to atomic nuclei and free to move around, which makes them easy to manipulate with electric fields and voltages. In contrast, bound charges are tightly bound to atomic nuclei and can only move within atoms. While these charges have been identified hundreds of years ago, they are not generally considered or applied when designing transistors or other electronic devices.

In their study, Prentki and his colleagues devised a method to engineer bound charges in electronic devices in an advantageous way. They refer to this design strategy as 'bound-charge engineering."

"Specifically, using Maxwell's equations, it can be shown that when an electric field traverses the interface between two materials, bound charge forms on that interface," Prentki said. "Furthermore, the amount of bound charge is proportional to the magnitude of the electric field, as well as the difference between the permittivities of the two materials. Permittivity is a material property that quantifies how much a material polarizes in response to an external electric field."

Prentki and his colleagues showed that surface bound charges at the interface between two regions of an electronic device can be controlled by tuning the electric field and choosing materials with suitable permittivity values. To create better tunnel field-effect transistors, the researchers propose surrounding part of the tunneling junction with a low-permittivity oxide, as this enables the formation of bound charge. In their paper, they considered this strategy for fabricating a transistor made of silicon nanowire.



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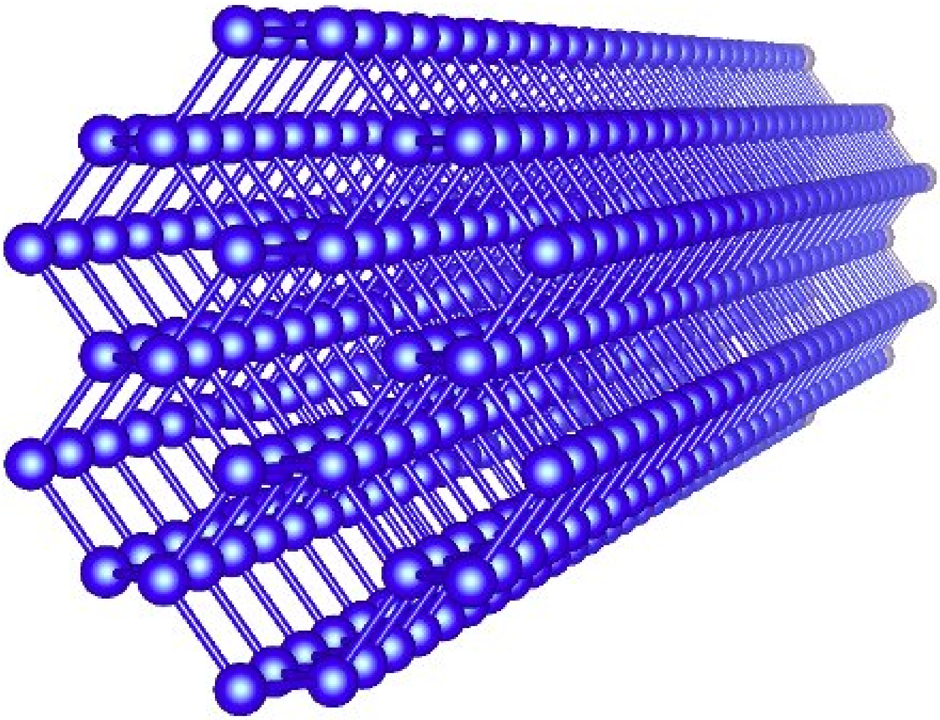
In existing state-of-the art transistor designs, the silicon nanowire is surrounded by an oxide with a high permittivity, such as hafnium dioxide, which enables a high gate capacitance. Prentki and his colleagues, on the other hand, propose the idea of surrounding the region of the nanowire close to the tunneling junction using silicon dioxide, an insulator with a value of permittivity that is only 3.8 times greater than the permittivity of air.

"In our design, the bound charge at the nanowire-oxide interface complement free charges in the screening effect, resulting in a sharper tunneling junction," Prentki said. "This results in a bound-charge-assisted tunnel field-effect transistor with an on-state current over 10 times higher than non-bound-charge-assisted transistors, which could enable its practical application in computing devices at higher clock frequencies."

Prentki and his colleagues showed that bound-charge engineering can be used to control the size of depletion regions at the junction between two regions of field-effect transistors. This is particularly true for the place where the "source" and "channel," or "channel" and "drain" regions of a field-effect transistor meet. In other words, bound charges can be used to support free charges in enabling a stronger screening effect in transistors.

"Our work introduces a general method to engineer bound charges to our advantage in materials and devices," Prentki said. "This is especially useful in emerging one-dimensional and two-dimensional materials. For example, bound-charge engineering offers significant performance boosts in silicon nanowire tunnel field-effect transistors."

In their recent paper, the researchers proved that their strategy for controlling the size of depletion regions can be used to improve the performance of a specific type of low-power field-effect transistor, namely, a tunnel field-effect transistor. In their next studies, they will experimentally test the feasibility of their strategy, using it to realize a real tunnel field-effect transistor.



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"Our investigation was purely simulation-based," Prentki explained. "Although we used a state-of-the-art simulation method, only a solid, real-world realization of the device can prove beyond doubt that the concept of bound-charge engineering really works."

In addition to proving the feasibility of bound-charge engineering for creating better performing tunnel field-effect transistors using nanowires, the researchers would now like to apply their strategy to other areas of nanoelectronics. For instance, they would like to test its effectiveness for downscaling specific types of transistors.

"Bound-charge engineering is a very general idea established by basic laws of electromagnetism," Prentki added. "Thus, in principle, it is not limited to applications in the fields of nanoelectronics and transistor design. Therefore, we would also like to apply this concept to other fields of research where bound charge and screening may be important, such as molecular electronics, electrochemistry and artificial photosynthesis."

More information: Nanowire transistors with bound-charge engineering. *Physical Review Letters*(2020). DOI: 10.1103/PhysRevLett.125.247704

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