(Invited) Where Are the Best Insulators for 2D Field-Effect Transistors?

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Abstract

Two-dimensional (2D) semiconductors are very promising for applications in next-generation field-effect transistors (FETs) which could overcome scaling limitations of Si technologies and thus extend the life of Moore's law. The success at achieving this ambitious goal will depend on the availability of compatible insulators which are always required to separate the gate from the channel. Ideally, these insulators should go along with 2D semiconductors as well as SiO_2 goes with Si. However, the research community is mostly focused on 2D semiconductors while not paying enough attention to finding suitable insulators for 2D FETs. In order to shed some light on this problem, here we formulate general requirements for insulators in 2D FETs and discuss the potential of already used and promising materials.

The scaling potential of 2D FETs can be fully exploited only if high quality insulators with an equivalent oxide thickness (EOT) below 1nm are available, as required for low subthreshold swings and reduced power consumption. This results in the following requirements for gate insulators: First, dielectric properties have to be good enough to maintain low tunnel and thermionic leakage currents to achieve high on/off current ratios. This implies high dielectric constants, wide band gaps and large band offsets with the channel material. Second, the insulator must form a well-defined interface with the channel, which is primarily required for a high mobility. Third, the number of active insulator defects within a few nanometers from the interface has to be low, in order to reduce charge trapping and thus maintain high stability of device operation. Finally, the insulators have to be electrically stable when scaled and survive electric fields of at least 10MV/cm.

Most previously reported 2D FETs employ conventional oxides (e.g. SiO_2, HfO_2, Al_2O_3) known from Si technologies. High-k oxides HfO_2 and Al_2O_3 appear to be the most promising, as they in principle satisfy the requirement on low leakage currents. However, they are amorphous when grown in thin layer, thus forming poor-quality interfaces with 2D channels, and contain numerous unavoidable insulator defects which lead to hysteresis and long-term drifts of the gate transfer characteristics. As a result, it appears to be unlikely that these materials can be considered promising for applications in future fully scalable 2D FETs.

In the spirit of Si technologies, a possible alternative to conventional oxides could be oxidation of 2D semiconductors to form native oxides, such as MoO_3 from MoS_2. While this may improve the interface quality, native oxides are still amorphous and sometimes non-stoichiometric, which leads to high densities of insulator defects and limited electric strength. Thus, considerable research efforts are still required to understand their potential.

Another possible solution is the use of layered 2D insulators. Their main advantage is their crystalline structure which leads to well-defined interface with 2D semiconductors and a low density of insulator defects. However, the most widely used 2D insulator is hexagonal boron nitride (hBN) which has a narrow bandgap (6eV) and a small dielectric constant (less than 5). This makes it difficult to maintain low gate leakage currents for hBN with sub-1nm EOT. Thus, alternative 2D insulators have to be urgently identified and characterized. Among these materials are mica, which outperforms hBN in terms of dielectric properties, and 2D oxide nanosheets. However, considerable processing advances are required to result in the demonstration of real devices.

Finally, another interesting option would be the use of ionic crystals, such as epitaxial fluorides (e.g. CaF_2, BaF_2, and LaF_3). Similar to 2D insulators, fluorides ideally contain a small number of defects and form well-defined interfaces with 2D semiconductors. Also, in contrast to hBN, they have good dielectric properties, e.g. a bandgap of 12.1 eV and a dielectric constant of 8.43 for CaF_2. Recently, excellent performance of MoS_2 FETs with 2nm thick epitaxial CaF_2 (0.9nm EOT) has been achieved, which is currently impossible with any other insulator discussed above. Thus, further research on these insulators appears a very promising way for the development of scalable 2D FETs.

In summary, the question about the most promising insulators for 2D FETs is still open. However, already now it is clear that successful integration of amorphous oxides into these devices appears problematic. Thus, it can be concluded that high-quality 2D FETs require crystalline insulators. These can be either layered 2D or ionic crystals with chemically inert surfaces, which generally address the fundamental limitations of oxides. Further research on these materials should target those which have the best dielectric properties and can be synthesized using fully scalable methods.