Novel materials for future transistor generations

Gennadi Bersuker *, Howard R. Huff

International SEMATECH, Austin, TX 78741, USA.

To meet the need for higher transistor speed while keeping power consumption under control, the semiconductor industry is working to introduce high-k gate dielectrics in leading-edge transistor manufacturing processes. However, these attempts are hampered by issues with high-k device performance, which were not fully anticipated at the start of high-k development. These issues may be of intrinsic material nature, process tool related, or related to material integration within the fabrication process. In addressing this question, the fundamental factors controlling the value of dielectric constants, along with the major factors determining integration of new materials into the mainstream manufacturing, are discussed in this presentation. Unlike conventional SiO_2 dielectric, where electronic polarization plays the major role in determining the dielectric constant, the most important contribution to the value of the dielectric constant in high-k materials comes from the dipole moment generated by appropriate ion displacements. It has become clear from extensive studies of a wide class of transition metal compounds that the driving force for large atomic displacements is a very specific feature of the d-electrons present in all high-k materials. The presence of the d-electrons affects most of the critical properties of high-k dielectrics. For instance, it leads to low-band offsets (with respect to the SiO_2 dielectric), which define the energy barrier for electron injection from the silicon substrate into the dielectric, as well as weakened covalent bonding that makes high-k materials more vulnerable to the formation of structural defects. The latter may be a source of fixed charges and/or electron traps adversely affecting mobility, threshold voltage, reliability, and other transistor characteristics. For the same reason, (diffused d-electrons), the transition metal compounds tend to form a long-range order that promotes crystallization of high-k dielectrics, which, among other negative properties, enhances ion diffusivity in the gate dielectric, and thus, their sensitivity to micro-contamination. The issues noted above and related structural features of the high-k dielectrics present serious challenges for their integration into the mainstream transistor manufacturing process. In summary, the presence of the transition metals, which facilitate higher k values, is also responsible for intrinsic material limitations. Many issues with high-k dielectrics are thus related to intrinsic fundamental properties. Successful integration of high-k gate dielectric materials must limit these undesirable features while retaining the material advantages.

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* Corresponding author. Tel. 512-356-7045.
Email address: `gennadi.bersuker@sematech.org` (Gennadi Bersuker).