High Performance High-k Gate Dielectrics Based on Mixed Oxides

Yue Kuo, Jiang Lu, Jiong Yan, Adam Birge, Chen-Han Lin, Somenath Chatterjee*,
Wen Luo**, Tao Yuan**, Jun-Yen Tewg***, and Way Kuo**
Thin Film Nano and Microelectronics Research Lab., Texas A&M University *Vellore Institute of Technology, India **University of Tennessee-Knoxville ***Intel Corp.

A high-k gate dielectric is required for nano-size MOSFETs because the thermally grown SiO_2 has many physical and fabrication limitations. Conventional high-k materials, such as HfO_2, ZrO_2, or Ta_2O_5, suffer from low crystallization temperatures, defective interface layers, small band gap energies, etc., which are due to thermodynamic nature. When the high-k film is prepared into a mixed oxide form, e.g., including a dopant element, many of the dielectric properties are improved. This kind of approach has been popular in recent years, as shown in the publication trend of Figure 1 (1). Varieties of dopants have been tested in these publications.

The dopant interferes the long-range order formation in the bulk film, which hinders the crystallization process as shown in Fig. 2 (2). The existence of dopant elements change the bond structure because different composing elements have different electron negativities, e.g., as shown in Fig. 3 (3). Dopant elements are often involved in interface reactions, which results in the formation of a metal silicate interface layer, as shown in Fig. 4 (3). There is evidence that dopant elements can hinder oxygen diffusion through the bulk film, which results in the thin interface layer (4). Further, the film's band gap can be affected by the dopant type and concentration, as shown in Fig. 5 (5).

The film's deposition process and method directly influence its structure and material characteristics and therefore, electrical properties. For example, the dielectric constant of TaO_x was enhanced with the addition of a proper amount of Hf, as shown in Fig. 6 (6). A sample with EOT 0.9 nm was prepared by the sputtering method (7). The thin doped film can have a leakage current 4 orders of magnitude lower than SiO_2 with same EOT, as shown in Fig. 7 (1). The breakdown strength can also be increased by doping (4).

Conditions of the deposition and post-deposition annealing processes are critical to the final device characteristics. The former affects the dopant concentration in the film and the interface damage mechanism. The latter affects the extent of oxygen deficiency, passivation of dangling bonds, oxygen diffusion rate, and reaction kinetics between the high-k film and the substrate. For example, the polarity and magnitude of the flat band voltage of the CVD HfO_2 film are different from those of the sputter deposited HfO_2 film. The doped film has a lower flat band voltage than the undoped film (1,8). The N_2 annealed film has a lower EOT but a higher leakage current than the undoped film, as shown in Fig. 8 (9). The doped high-k film has a much larger relaxation current and different 2-step breakdown sequence from the SiO_2 film (10). Sometimes, an artificial SiO_2 interface layer was inserted between the doped high-k film and silicon wafer to achieve a low interface state density. However, our new result shows that when the post deposition annealing condition is set properly, e.g., a short injection of O_2 in the atmosphere, the low interface density can be obtained without an artificial interface layer.

In summary, the mixed oxide high-k film is a more viable gate dielectric material than the conventional metal oxide film because of flexibility in controlling various material and electrical properties.

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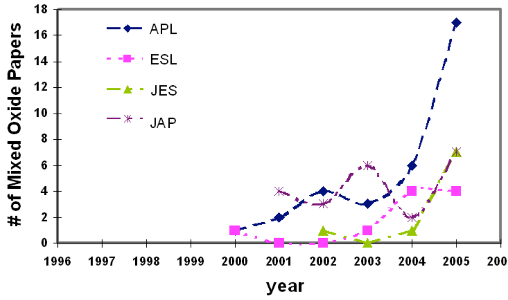

Fig 1. Number of mixed oxide high-k papers published from 2000 to 2005 (1).

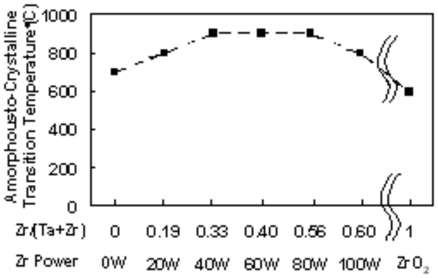

Fig. 2(b). Crystalline temperatures of Zr-doped TaO_x films (2).

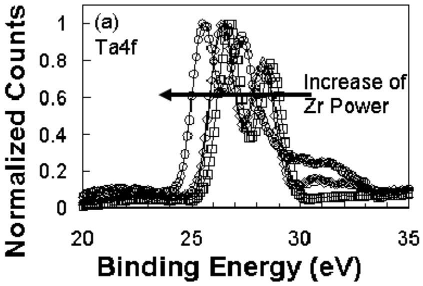

Fig. 3. XPS of Zr-doped TaO_x films (3).

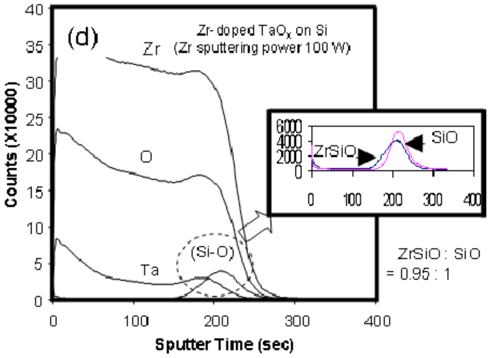

Fig. 4. SIMS profiles of Zr-doped TaO_x (3).

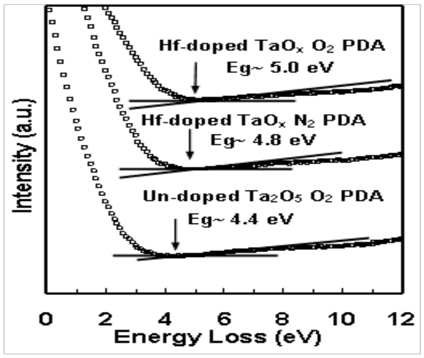

Fig. 5.Band gap energies vs. dopant concentration (5).

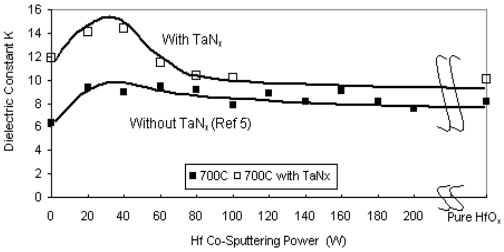

Fig. 6. Apparent k values of Hf-doped TaO_x with and without a TaN_x interface layer (6).

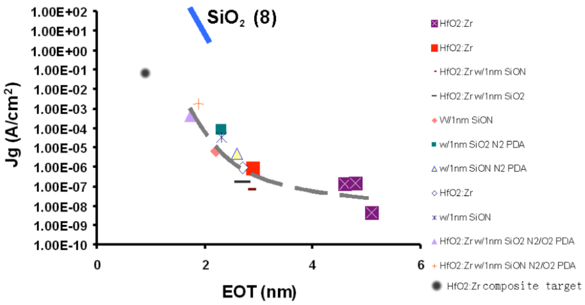

Fig. 7. Leakage currents of Zr-doped HfO_2 films (1).

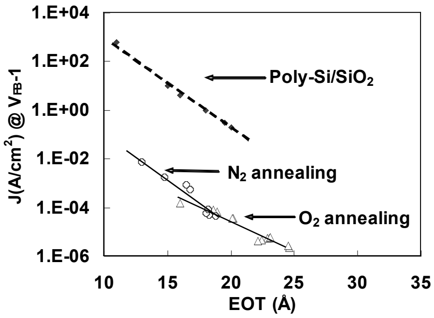

Fig. 8. Post deposition annealing atmospheres influence on leakage current (9).