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SHORT COMMUNICATION

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Three-dimensional electrostatic capacitors as futuristic miniaturized energy storage component for energy autonomous systems

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Abstract

For the integration of ambient energy sources into implantable/wearable microelectronics, the development of efficient and high-power energy storage devices is essential (such as electrostatic or dielectric capacitors). In light of the general need for small components for energy storage devices, the development of fluorite-based three-dimensional structured electrostatic capacitors is expected to open new paths for the future development of on-chip energy storage, especially because of their enhanced capacity at low deposition thicknesses (in nanometers).

KEYWORDS

3D structures, dielectrics, electrostatic capacitors, energy storage, microelectronics

The trend toward the integration of ambient sources of energy into wearable and portable devices has inspired much interest in the development of efficient and high-power energy storage devices. Ambient energy sources, such as thermal, wind, vibration, and solar, have time-dependent profiles as harvestable energy depends on many factors, including weather conditions, time of day, and time of year.[1] Therefore, energy storage devices should have high energy storage density and high-power density. These energy storage devices have the capability to respond very rapidly, so energy should be stored as it is harvested, while also being distributed as rapidly as desired. Supercapacitors (electrochemical capacitor [ECC]) and lithium-ion (Li-ion) batteries are two preferred candidates for energy storage applications.[2,3] Although they have high energy storage densities, their power densities are very low, which limits their incorporation with ambient energy sources and wearable or portable devices.

An electrostatic capacitor (ESC) may also be a viable candidate as an energy storage device for future applications. They have high-power densities but low energy storage densities because the energy storage process is primarily achieved with surface charges. Due to the low energy densities of ESCs, they are mainly used as electronic components in the microelectronics industry rather than as energy storage devices.

Recent developments in nanotechnology, especially in three-dimensional (3D) nanostructures (such as self-rolling, anodized aluminum oxide, and Si nanotrenches), have enabled significant expansion in the effective area of a capacitor, which greatly enhances their potential for energy storage applications.[4] To date, atomic layer deposition (ALD) is the leading process used to attain uniform and conformal growth of electrode and dielectric layers with thicknesses of several nanometers in 3D nanostructures. Note that conventional dielectric materials (such as polymers, lead-based ceramics, and lead-free ceramics) are not appropriate for 3D nanostructures.[5] The major hindrance to the use of these conventional materials in 3D nanostructures lies in the technical difficulty involved in their deposition with a high aspect ratio using the ALD technique.

Aluminum oxide (Al_2O_3) is a linear dielectric that can be used in 3D structures. It has a high dielectric constant, a large bandgap, and a highly matured ALD process. In 2009, Banerjee et al. fabricated a 3D ESC ($TiN/Al_2O_3/TiN$) in an anodized aluminum oxide nanostructure using ALD.[6] Their ESC had an energy storage density of 0.7 Wh/kg and a power density of ~10^6 Wh/kg, which were limited due to the breakdown field (~4 MV/cm). The energy storage capability of a 3D Al_2O_3-based capacitor is comparable to those of ECCs while being far higher than those of conventional ESCs. Nonetheless, the energy storage density of Banerjee's 3D ESC is still lower than those of batteries and fuel cells. Later, Haspert et al. improved the breakdown field of this ESC from 4 to 10 MV/cm by nanoengineering of the anodized aluminum oxide 3D structures, which consequently improved the energy storage density to 1.5 Wh/kg.[7]

Recently, fluorite structured materials (eg, ZrO_2 and HfO_2) were reported to have antiferroelectric properties, which are very suitable for energy storage applications.[8,9] A Si-doped HfO_2-based planar ESC indeed exhibited high energy storage and power densities of ~1.9 Wh/kg and ~10^9–10^{10} Wh/kg, respectively, at 4.00 MV/cm, which are higher than those of Al_2O_3-based 3D ESCs.[4] However, the energy storage density of the Si-doped HfO_2-based ESC will be improved if its structure is converted from planar to 3D form to increase the effective area. In 2016, a ZrO_2-based 3D-structured ESC was reported to showcase the best performance in energy storage density (~900 J/cm^3).[10] The gravimetric energy storage density of ZrO_2 can be calculated from the given equation:

$$\text{Gravimetric energy storage density} = \frac{\text{Volumetric energy storage density}}{\rho},$$

where ρ is the mass density of the material. The unit of gravimetric energy storage density is Wh/kg. The calculated gravimetric energy storage density of the ZrO_2-based 3D capacitor is ~45 Wh/kg. The calculated energy storage density is larger than those of conventional ECEs and ECCs, while being comparable to those of Li-ion batteries. In addition to the advantages of high energy and power densities, the application of ZrO_2-based materials to the fabrication of nanoscale ESCs is highly feasible (Figure 1).

The recent trend in the development of implantable, portable, and wearable electronics devices continuous miniaturization accompanied by improvement in the reliability and functionality of existing electronic components. Nonetheless, the integration of conventional energy storage elements (eg, ECCs and batteries) with circuits is quite challenging. Thus, integration is often the limiting factor in miniaturization of the entire electronic system. In light of the general need for small components for energy storage devices, the development of fluorite-based 3D structured ESCs is expected to open new paths for the future development of on-chip energy storage, especially because of their enhanced capacity at low deposition thicknesses (in nanometers). Further, when one considers the short lifetime of conventional storage media, ESCs with unlimited lifetime may be an effective game-changer in implementing implantable energy storage device applications.

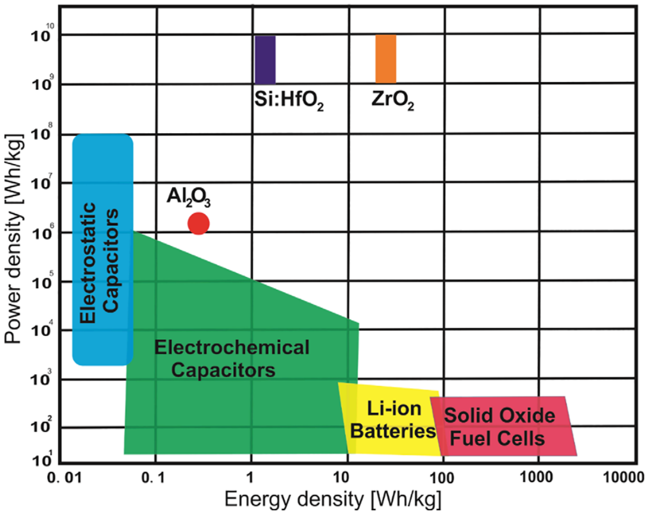

FIGURE 1 Comparison of energy storage technologies

1 | CONCLUSION

In summary, 3D ESCs based on fluorite-structural materials have high energy storage as well as high power density. The gravimetric ESD of the ZrO_2-based 3D capacitor was ~45 Wh/kg, which is comparable to the ESD of Li-ion batteries. Due to the small deposition thickness of the fluorite-structural materials, these materials can be very feasible for the fabrication of the nanocapacitors, which can be used as an energy storage component for the implant and wearable electronic devices.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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