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Fabrication of precision integrated capacitors

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ABSTRACT

A detailed parametric study on the fabrication of metal-insulator-metal capacitors through the anodization of aluminum in an aqueous ammonium pentaborate octahydrate electrolyte is reported. The dependence of the specific capacitance on anodization voltage (8 V–30 V), time (5 min–60 min), temperature (5 °C–60 °C) and electrolyte concentration (0.01 M–0.05 M) was studied in deionized water and ethylene glycol. A linear increase in capacitance with anodization voltage was found, with the highest capacitance achieved at 473 nF/cm^2 in ethylene glycol. Room temperature, long-time anodization time and high electrolyte concentration within the studied range yielded the best quality dielectric films. The leakage current was <1 nA/cm^2 when the dielectric was formed in ethylene glycol. The capacitors fabricated in ethylene glycol satisfy the on-chip capacitors criteria of the International Technology Roadmap for Semiconductor, with quadratic voltage coefficient < 100 ppm/V^2.

1. Introduction

Integrated, mass formed, passive components in electronic package substrates or printed wiring boards allow for denser electronic systems [1]. Among the most common passive components, capacitors are of high interest because of the number of components used on the substrate for power-ground decoupling, filtering and noise suppression [2–4]. Directly incorporating the capacitor into the substrate, compared to surface mounting, can free-up surface area for other components and decrease the parasitic properties caused by the mounting technology [5].

The capacitor dielectric material can be divided into paraelectric and ferroelectric materials. Both types of dielectric materials experience electronic, ionic and atomic polarization [6]. Ferroelectric materials retain their polarization when the external field is removed, because atoms cannot move within the lattice [6]. However, the dielectric properties of ferroelectric materials depend strongly on temperature and frequency, which is a disadvantage at high frequency application. Paraelectric materials such as SiO_2 [7], Si_3N_4 [7], TiO_2 [7,8], Al_2O_3 [7,9], Ta_2O_5 [7,10], and many polymers and polymer nanocomposite [1,11,12] have relatively low dielectric constant compared to ferroelectric materials, however, they can operate consistently over a wide range of temperatures and frequencies, which make them useful for capacitors. Among all the paraelectric materials, inorganic thin-film oxides made from valve metals (e.g. aluminum, vanadium, zirconium, hafnium, tantalum, tungsten, etc.) stand out because they can be formed at low temperature with consistent performance using a variety of techniques. Aluminum oxide is often chosen as the dielectric because aluminum metal is inexpensive, relatively malleable, and is easy to deposit by evaporation or sputtering, which is compatible with different applications.

Many techniques have been used to produce aluminum oxide thin films, including plasma oxidation [13], ozone oxidation [14–16], reactive ion beam sputtering [17], e-beam evaporation [18], and atomic layer deposition of the oxide itself [19,20], etc. Among these, anodic oxidation is attractive because the processing can be done at low cost and low temperature. Further, the processing conditions can be easily controlled.

There have been numerous studies of the process conditions and quality of anodic aluminum oxide (AAO) films produced from different electrolytes. Nelms et al. used tartaric acid neutralized with ammonium hydroxide to achieve low leakage current and low defect density, with specific capacitance < 100 nF/cm^2 [9]. Diesing et al. used an acetic acid buffer to create capacitors with specific capacitance of 1260 nF/cm^2 with low breakdown voltage and high leakage current [21]. Kaltenbrunner et al. used citric acid electrolyte to achieve 420 nF/cm^2 specific capacitance [22], but resulted in high leakage current [23]. Mardare et al. used a neutral electrolyte to achieve 850 nF/cm^2, but with high leakage current [24]. Oh et al. used ammonium adipate to achieve low leakage current, with low specific capacitance, <65 nF/cm^2 [25]. Ban et al. demonstrated the fabrication of capacitors using boric and citric acid, with 580 nF/cm^2 and breakdown voltage of 530 V [26]. Dickey et al. performed a two-step anodization by using sulfuric acid and boric acid to demonstrate high breakdown voltage, but low specific capacitance of 20.8 nF/cm^2 [27]. Hourdakis et al. also

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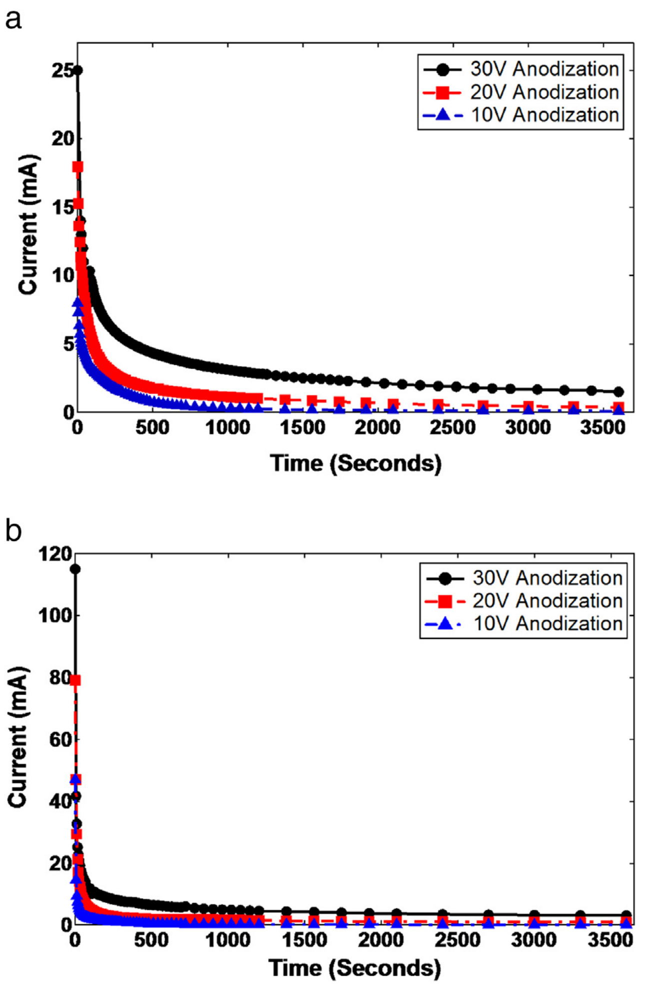

Fig. 1. Current vs. time profile for anodization at 10 V, 20 V and 30 V in (a) ethylene glycol, (b) DI water.

performed a two-step anodization using sulfuric acid and citric acid to achieve low leakage current but with low specific capacitance, 7.2 nF/cm^2 [28].

Studies on usage of ammonium pentaborate octahydrate (APO) as the anodizing electrolyte have shown a better balance between leakage current, specific capacitance, operating voltage and capacitance accuracy. An aqueous solution of APO has a near-neutral pH so that the dissolution of the oxide is minimized during anodization. Ajit et al. used APO as the electrolyte for anodization at relatively high voltage and demonstrated high specific capacitance with low leakage current [29]. Rao et al. used an APO electrolyte to obtain specific capacitance up to 3000 nF/cm^2, with low dielectric loss, and consistent capacitance up to 1 MHz [30]. More recently, Kanadassan et al. used APO as the electrolyte and achieved a specific capacitance of 600 nF/cm^2 that was not sensitive to operating temperature and frequency [31]. Although specific results have shown promise, a comprehensive study of the fabrication parameters including anodization solvent, anodization time, anodization

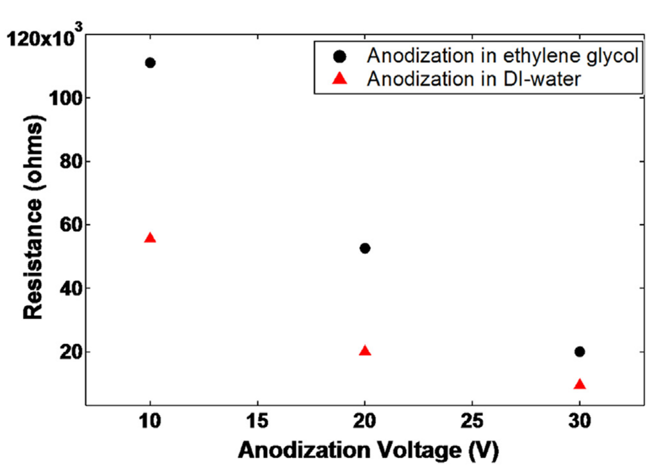

Fig. 2. Film resistance vs. Anodization voltage in ethylene glycol and DI water.

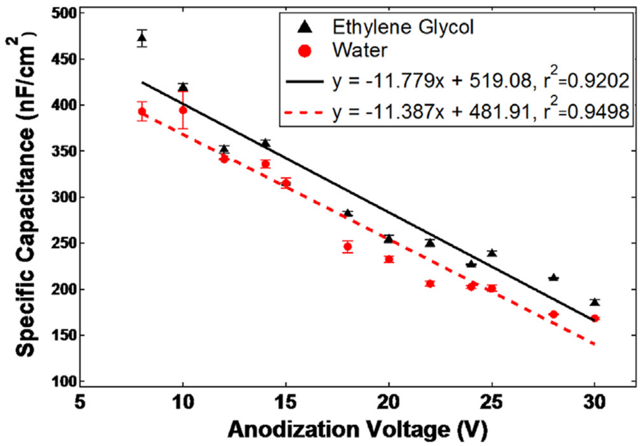

Fig. 3. Specific capacitance of capacitors fabricated in DI water and ethylene glycol vs. anodization voltage.

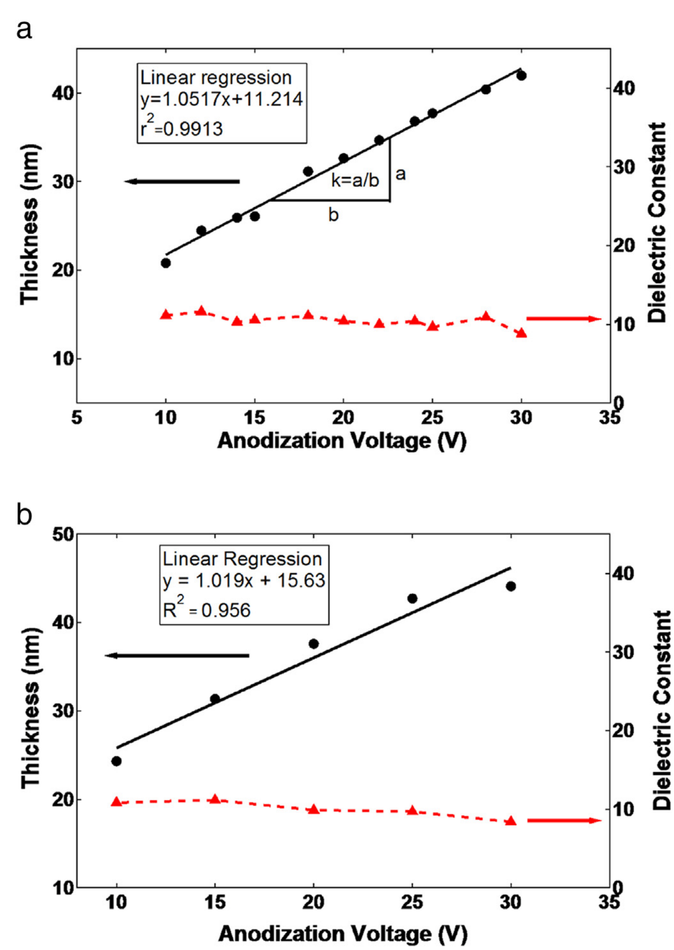

Fig. 4. Thickness and dielectric constant of AAO films anodized in (a) ethylene glycol, (b) DI water.