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Built-in self-limitation of masked aluminum anodization using photoresist

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Abstract

This paper reports on a simple method for wafer-scale production of precisely-shaped 2D patterns of porous anodic alumina (PAA) by masked anodization of aluminum films. The produced dielectric PAA structures, featuring cylindrical nano-pores of very high aspect ratio (>100), are useful for several applications including the production of nanowires and miniature MEMS packages. The fabrication process utilizes a photoresist mask; but to overcome the instability of the photoresist during the anodization process, special borderlines are included in the mask design. These borderlines act as self-synchronized switches for the anodization current, preventing the undesired photoresist delamination and lateral extension of the PAA structures. Employing such borderlines resulted in a reduction of the lateral extension of masked Al anodization on 200 mm wafers from more than 300 µm to approximately 6 µm.

Keywords: Porous alumina; Masked anodization; Wafer-scale electrochemical processing; Nanowires; MEMS packaging

1. Introduction

Porous anodic alumina (PAA) films of virtually any thickness can be produced by anodization of Al in certain low-pH electrolytes [1]. These oxide films distinctively feature cylindrical nano-pores of very high aspect ratio [1,2]. This unique structure, in addition to the associated low dielectric constant, is appealing for several applications such as 3D nano- and micro-structures fabrication [2,3], advanced IC interconnects [4], and thin film packaging of MEMS [5,6]. Patterned PAA films are usually produced by

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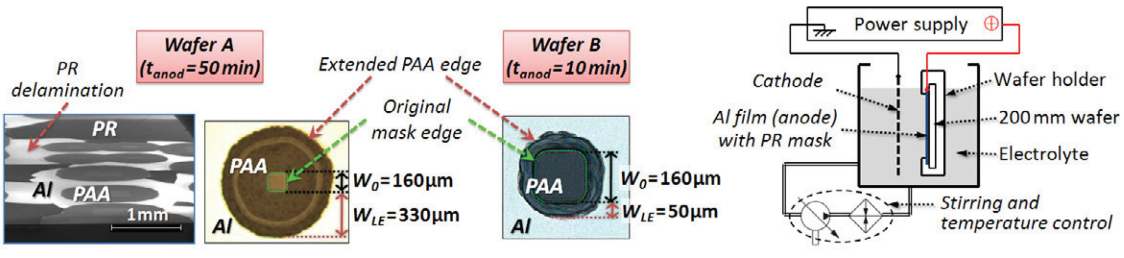
means of a hard mask that is made of a chemically-resistant thin film such as silicon dioxide or niobium [3,4]. Alternatively, a simpler approach utilizes a photoresist (PR) mask [5,6]; this way eliminating the processing steps needed for the hard mask deposition, patterning and removal.

Photoresists used nowadays for electrochemical processing are however not very stable during the Al anodization process for producing patterned PAA films. The photoresist eventually delaminates due to chemical reaction with the anodization electrolyte, formation of gas bubbles, or volume expansion of the Al layer during the anodization process. This leads to an undesired continuous lateral extension of the PAA structures as shown in Fig. 1(a,b). In this paper we present a simple technique to overcome this shortcoming of photoresist-based masked anodization. The technique makes use of a special design of the photoresist mask in which *borderlines* are introduced to limit the undesired lateral extension of the anodization process.

2. Self-limiting masked anodization process

The principle of operation of our wafer-scale anodization setup is similar to that of an electroplating setup (see Fig. 1(c)). The electrical connection between the power supply and the Al film is established through a number of contact electrodes in the wafer holder, facing the outermost rim of the front-side of the wafer. The anodization electrolyte is based on diluted sulfuric acid (10% acid content by volume) kept at a constant temperature in the range 20-30 °C. The layer to be anodized is a 1 µm-thick Al film, sputtered on top of a 200 mm Si wafer covered by a dielectric thin film such as silicon dioxide. The anodization mask is produced using a 7 µm-thick layer of a photoresist which is designated for electrochemical processing. The anodization potential is typically 20 V.

Figure 2 illustrates the current flow and PAA growth scheme during Al film anodization using either a conventional mask design (Fig. 2(a)) or an improved design involving borderlines that surround each group of the intended PAA patterns (Fig. 2(b)). Initially, the PAA film grows vertically towards the lower surface of the Al layer within the boundaries defined by the photoresist mask. In a later phase, the PAA structures start to grow laterally beyond the mask edges due to the localized damage to the photoresist edges and the continuous current supply from the wafer perimeter (see Fig. 1(a,b) and Fig. 2(a)). However, if borderlines are employed, the lateral PAA growth is restricted only to the outer edge of the borderlines. This is attributed to the fact that the anodized (oxidized) borderline prevents any further supply of electrical current to the enclosed PAA structures once the vertical anodization phase is complete (see Fig. 2(b)). Therefore, the borderlines act as self-synchronized OFF switches for the anodization current.



(a) (b) (c)

Fig. 1. The conventional process of photoresist-based masked anodization of Al thin films on top of an insulating layer on 200 mm wafers: (a) Tilted-view SEM and top-view photomicrograph of *Wafer A* (anodized for 50 minutes) showing the photoresist delamination and the resulting large lateral extension (W_{LE}=330 µm) beyond the original mask edge (W_0); (b) Top-view photomicrograph of a PAA structure of another sample (*Wafer B*) which is anodized for 10 minutes, resulting in lateral extension of approximately 50µm; (c) Schematic illustration of the anodization setup used in this work.

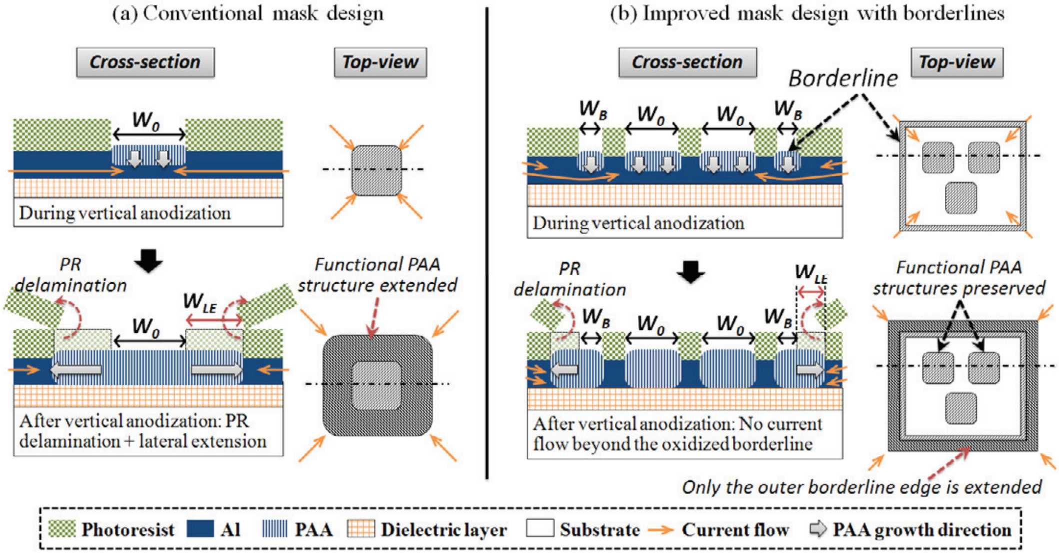
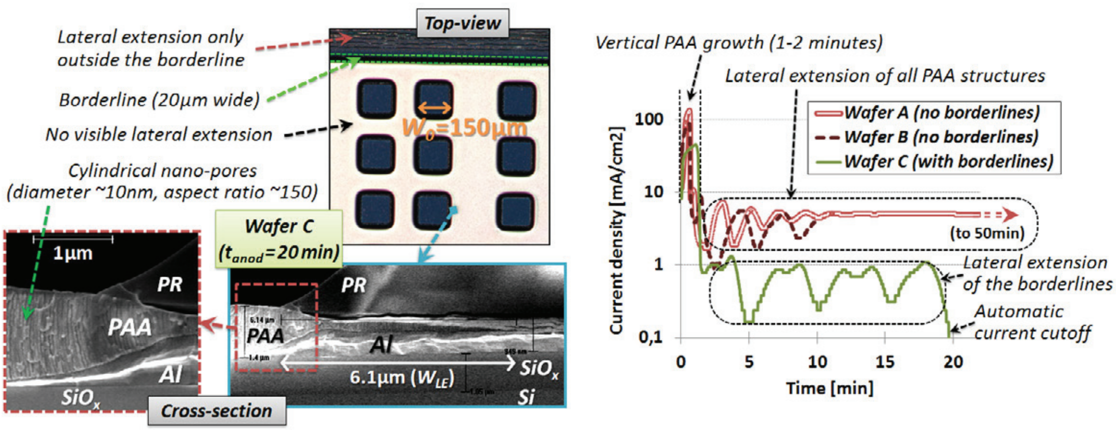


Fig. 2. Schematic illustration of the two main phases (vertical anodization and lateral PAA extension) of photoresist-based masked Al anodization: (a) Using a conventional mask design leading to lateral extension (growth) of the PAA structures after completion of the vertical anodization phase; (b) Using an improved mask design featuring a borderline which acts as a self-synchronized switch for the anodization current, preventing any undesired lateral extension of the PAA structures surrounded by such borderline.

3. Results and discussion

The results of employing borderlines in the mask design for thin film Al anodization are shown in Fig. 3(a). The improved design includes borderlines of 20 μm width (W_B), enclosing every group of patterns within an area of approximately 46 mm^2. A spacing of 200 μm separates adjacent borderlines to



(a) (b)

Fig. 3. (a) Photomicrograph and SEM's showing the results of implementing the borderlines design in photoresist-based masked anodization (for 20 minutes) of an Al thin film on *Wafer C* (lateral extension of a 150 μm-wide functional PAA structure is limited to a thin PAA tail of 6.1 μm width); (b) Current density evolution during anodization at 20 V potential of the 3 samples discussed in this work (see also Fig. 1). For *Wafer C*, an automatic current cutoff is reached within approximately 20 minutes.

facilitate the anodization current flow throughout the wafer. Precise confinement of the produced PAA film patterns by the photoresist mask is obtained. Only a thin tail of PAA extends for a distance of 6.1 μm beyond the mask edge. Considerable lateral extension of the anodization process occurs only outside the edges of the borderlines, causing no negative impact on the functional PAA structures.

The current density evolution curves in Fig. 3(b) further illustrate the advantage of using the borderlines design. *Wafer A* and *Wafer B*, which employ a traditional mask design, suffer from a continuous (laterally extending) anodization process until the power supply is manually switched off after 10 and 50 minutes, respectively. In contrast, *Wafer C*, featuring the borderlines design, displays a more limited lateral extension of the anodization process. This is followed by an automatic current cutoff within 20 minutes as a result of oxidizing all the Al structures located outside the borderlines.

4. Conclusions

A simple technique has been demonstrated for precise local anodization of Al thin films on 200 mm wafers using photoresist as a masking layer. The process is based on standard CMOS materials and techniques, and is advantageous in terms of cost and manufacturability as compared to a process that is based on a hard mask. By introducing 20 μm-wide borderlines to the photoresist mask design, a built-in self-limitation of the anodization process is achieved. This results in an automatic current cutoff within 20 minutes and less than 10 μm lateral extension of the functional PAA structures. The proposed technique provides a simple local anodization process by eliminating the need to establish a critical balance among the different process parameters, including the exposed Al area, the Al layer thickness, the anodization potential, the composition of the electrolyte, the temperature, and the process duration. Finally, the specific geometrical design of the borderlines and the anodization process parameters can be further optimized for more stringent control over the edge profile of the PAA structures if needed.

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