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Study of electrical current reconstruction on macropore arrays etched electrochemically on lightly-doped n-Si

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ABSTRACT

Silicon macropore arrays are fabricated on lightly-doped n-Si by electrochemical etching. The opening diameter, inner diameter, and wall thickness of the macropores are observed to depend on HF concentration and current. A current reconstruction model is proposed to elucidate the formation mechanism of the macropores. Two geometric models are established for the silicon macropores according to the experimental results. The finite element method is used to simulate the electric field and current in the electrolyte-silicon system. The reconstruction of electrical current on the silicon macropore arrays is described by simulating the electric field and current. The ratio of major to minor semi-axes of the elliptical pore (b/a) decreases with increasing the ratio of diameter to wall thickness as confirmed experimentally. The results indicate that the b/a ratio is correlated with the HF concentration and applied voltage.

1. Introduction

Lightly-doped silicon with resistivity larger than kΩ cm provides a large space charge region (SCR) and is suitable for the fabrication of silicon macropore arrays (SMPAs) with diameter and wall thickness larger than 10 μm [1–7]. The SMPAs with special materials filled pores have potential applications in the detection and imaging of such high energy particles as thermal neutron, X-ray. [7–10]. The geometric shape of the macropores plays an important role in the structural control in an electronic device, and filling and doping the pores sometimes encounter problems arising from non-uniformity [5–8]. Kleimann et al. prepared SMPAs with macropores lager than 20 μm and concluded that the wall thickness could not extend over 30 μm [3,4]. Badel et al. reported macropore arrays with a pore size of 10 μm and spacing of 50 μm in the solution of HF:H_2O (v/v) = 4:40 [5,6]. This means that the mechanism of macropore formation is not well understood, although the effects of electrolytes and currents on the macropores have been studied [1–7,11–15].

Formation of silicon macropore arrays (SMPAs) on silicon by electrochemical etching in a solution containing hydrogen fluoride (HF) has been studied since the 1990s [1,2,16]. The space charge region (SCR) and current burst model (CBM) are used to explain the etching process on lightly-doped silicon [1,2]. The SCR effect which has been supposed to be responsible for pore-wall passivation is more controversial because the pore size and wall thickness are found to be affected by the applied voltage, illumination, and electrolyte [11–21]. The CBM taking into consideration the effect of the electrical currents constitute the SCR model to explain the mechanism of pore formation. The current at the macropore tip should be equivalent to that of electrochemical polishing of silicon according to CBM [14–16], but the CBM model does not provide a description of the pore shape and size. With regard to prepatterned pores, the diameter of the prefabricated pits and spacing are determined by prepatterning. The pore structure morphs from an inverted pyramid to a deep hole during the etching process thereby indicating reconstruction of current. Experimentally, the pore shape and spacing are usually altered by changing the HF concentration and applied voltage [5–7] and hence, it is useful to control the silicon macropores by studying the ratios of diameter to spacing and major to minor semi-axes of the elliptical bottom of the macropores.

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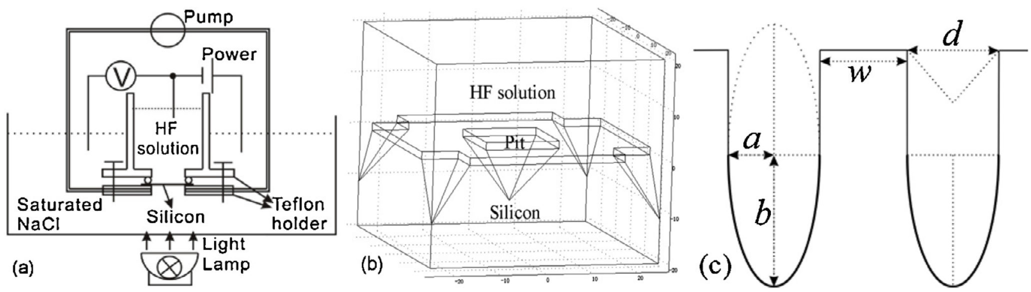

Fig. 1. Schematic of the experimental setup for etching silicon (a), 3D model of prefabricated pits (b) and 2D model of macropore arrays (c) for COMSOL Multiphysics simulation.

The current under the conditions of under-etching of silicon close to the mask has been simulated by the finite element method which is embedded in COMSOL Multiphysics [22]. This work aims at elucidating the etching mechanism from another perspective. The geometric shape, diameter, and wall thickness of the macropores are employed to discuss reconstruction of the electrical current on the lightly-doped silicon experimentally and theoretically. The silicon macropores arrays are prepared using different HF concentrations and applied voltages and COMSOL Multiphysics is used to calculate the electric field and current on the silicon surface in the electrolyte-silicon etching system. The ratios of the diameter to spacing and major to minor semi-axes of the elliptical bottom of the macropores are discussed.

2. Experimental details

The SMPA was prepared on polished 4–5 kΩcm n-type (1 0 0) Si wafers approximately 380 μm thick. A surface oxide was grown and then arrays of windows with a size of 15 μm × 15 μm, spacing of 35 μm in row and 10 μm between the rows were patterned to initialize the pore opening and position. The patterns between two close rows are arranged alternatively as depicted in Figs. 1–4. Pits of inverted pyramids were prefabricated by anisotropic etching in 22% TMAH solution at 90 °C. The size of the prefabricated pit was 16 μm × 16 μm and the spacings were 34 μm in row and 9 μm between the rows after TMAH etching. Electrochemical etching took place in hydrofluoric (HF) acid and the deep macropore array was formed by an anodic bias. The experimental setup for etching silicon was shown in Fig. 1(a). A halogen lamp located at the backside of the etched face was rated at 50 W/220 V. The light intensity was controlled by a rheostat and the applied voltage of the lamp was 145 V during the etching process. The distance between the silicon wafer and lamp was 10 cm. The cell was made of Teflon and a saturated NaCl solution was used as the backside contact of the silicon. A peristaltic pump was used to circulate the NaCl solution to eliminate bubbles and heat generated at the contact interface. The voltage was measured by an extra voltage meter in an independent circuit to avoid interference from the contact voltage between the electrode and electrolyte. The electrodes put into the NaCl solution and HF electrolyte for etching and measurement were platinum slices. The electrolytes for etching silicon were prepared by mixing de-ionized water and hydrofluoric acid (49%HF). All the samples were etched electrochemically for 2 h at room temperature.

3. Finite element simulations

The formation process of SMPA can be divided into two steps. One is etching of the prefabricated pits on silicon in the beginning and the other is reconstruction of the pore shape, diameter, and wall afterwards. Both these two factors affect the morphology of SMPA. The etching system of silicon and solutions under

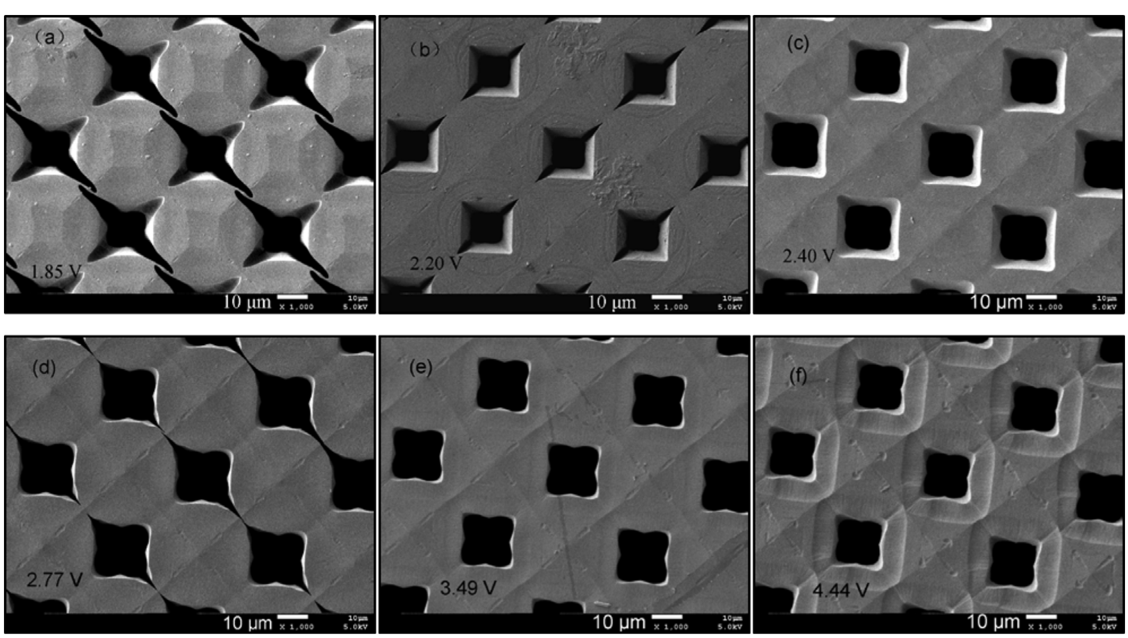

Fig. 2. Surface images of the SMPA etched at 1.85 V (a), 2.20 V (b), 2.40 V (c), 2.77 V (d), 3.49 V (e) and 4.44 V (f) in 5.1% HF solution.

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