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Formation of nanometer-scale gap electrodes based on a plasma ashing technique

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Abstract

We propose a new and reproducible method to fabricate metal electrodes with a nanometer-scale gap and width, which have been considered as one of the basic building blocks for future nano-devices. The techniques used in this study were the conventional photolithography, e-beam lithography and plasma ashing techniques. Specifically, the plasma ashing process was used to easily form the nanometer-sized gap (10 nm or less) that is difficult to realize by e-beam lithography only. Using the method investigated in this work, we demonstrated that Au electrodes with a nanometer-sized gap and width could be easily fabricated.

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Keywords: Electrode; PR ashing; e-beam lithography; Nano-device

1. Introduction

Reliable nano- [1–3] and bio-electronic [4–7] devices require the formation of metal electrodes with nanometer-scale gaps. Recently, the fabrication of metal electrodes with the nanometer-sized gap has been demonstrated by using advanced techniques such as electron-beam (e-beam) lithography [1–5,8,9] and focused ion beam (FIB) lithography [10,11]. It is known that the formation of electrodes with the nanometer-sized gap as short as 5 nm are feasible when e-beam lithography is employed. Although either e-beam or FIB lithography demonstrates the ability to form the nanometer-scale gap, the problems of throughput and reproducibility have to be solved. Recently, various techniques such as electro-migration-induced break junction [1], shadow deposition [4,5] and electrochemical deposition [6–12] have been proposed to further reduce the nanometer-scale gap fabricated initially by either photolithography or even e-beam lithography. However, most of these techniques are too difficult to obtain reliable metal electrodes with the nanometer-sized gap in the range of 10 nm or less, and most importantly are not appropriate to apply for mass production. Recently, we proposed a new and reproducible method to fabricate Au electrodes with a nanometer-scale gap using a photoresist (PR) ashing technique, and demonstrated that metal electrodes with a nanometer-scale gap (e.g., 10 nm or less) can be easily formed without employing e-beam lithography [13]. Although, using the PR ashing technique, the control of gap distance to the nanometer scale was easy and reproducible, the realization of metal electrode with the nanometer-scale was rather difficult to achieve. In this article, we propose a new method to form Au electrode with both nanometer-scale gap and width. Specifically, the PR ashing and e-beam lithography techniques are used for the purpose of reducing the nanometer-scale gap and width, respectively.

2. Experiment: formation of nanoelectrodes

A procedure for fabricating Au electrodes with nanometer-scale gap and width is shown in Fig. 1. Positive AZ 1512 photoresist (Clariant Co.) was spin-coated on the thermally oxidized p-type (100) silicon substrate to a thickness of 1.35 ± 0.02 μm. The gap size on a photo mask was in the range of 200∼1000 nm. The substrates were then exposed

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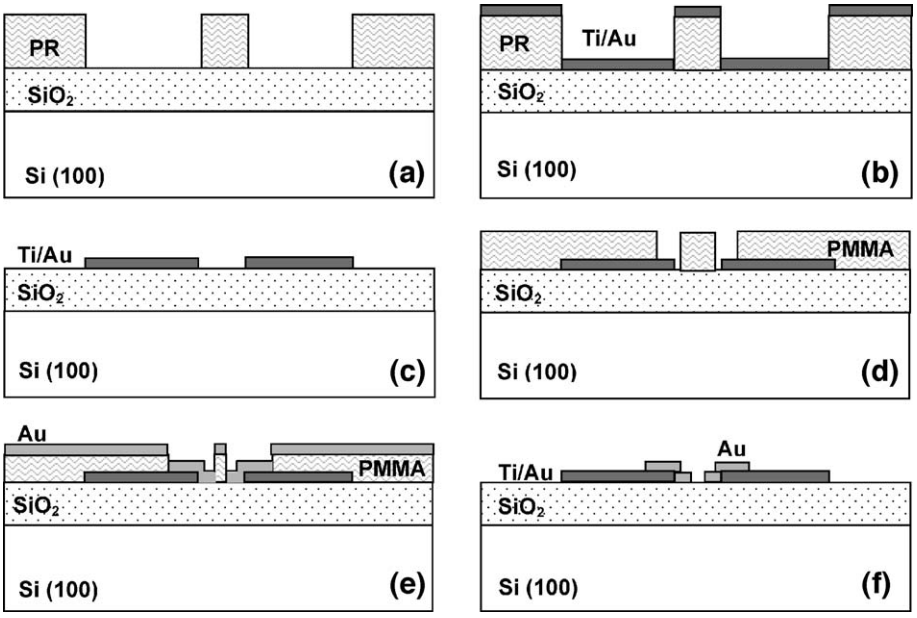

Fig. 1. Procedure for fabricating Au electrodes with nanometer-scale gap and width: (a) positive photo resist (AZ 1512) film was exposed by optical lithography (*i*-line wavelength), and was developed using AZ 500 MIF developer. (b) Ti and Au films were successively deposited using an evaporator. (c) Liftoff process of the AZ 1512 PR defines both pad and electrode. (d) PMMA was exposed using e-beam lithography, and then developed with MIBK : IPA (1 : 3) solution. (e) Both length and height of developed PMMA film was reduced using a plasma downstream asher. Then a thin layer of Au was deposited for the second liftoff step. (f) Liftoff process of PMMA defines Au electrodes with nanometer-sized gap. The size of gap can be easily controlled via a proper selection of the ashing conditions.

using a mask aligner with *i*-line wavelength (345 nm) at 12 mW, and were developed using AZ 500 MIF developer (Clariant Co.). A cross-sectional view of the patterned substrate is shown in Fig. 1(a). After a developing procedure, a thin adhesion Ti layer (10 nm) was deposited using an e-beam evaporation technique at 10^{-6} Torr, and Au films were then deposited on Ti in situ using a thermal evaporation method [Fig. 1(b)]. A liftoff process results in the first electrode pattern as shown in Fig. 1(c). Both e-beam lithography and PR ashing techniques were used to minimize the width and gap of Au electrode, respectively. The e-beam resist was polymethyl methacrylate (PMMA). PMMA (950 K, 2%) was spin-coated on the substrate [see Fig. 1(c)] to the thickness of 200 ± 10 nm, and the samples were baked for 2 min at 180 °C in an oven. The samples were exposed using the electron beam with the dosage of 350 μC/cm^2 [JEOL 6460 scanning electron microscope (SEM) with an Elphy Plus controller (Raith Co.)], and then developed for 90 s using MIBK : IPA (1 : 3) solution. Fig. 1(d) represents a cross-sectional view of the developed pattern. Both length and height of the developed PMMA patterns were reduced using a plasma downstream asher (a modified dry etcher: Tokuda Co., CDE-7-3). Detailed procedures for the PR ashing were given in Ref. [13]. The pressure of the reaction chamber was 0.1 mTorr, and the frequency and power of the applied microwave were 2.45 GHz and 1.5 kW, respectively. The processing gases used in this study were consisted of oxygen (1500 sccm), nitrogen (500 sccm) and carbon tetrafluoride (CF_4 100 sccm). After completing the PR ashing process, Au film was deposited using the thermal evaporation method to the thickness of 200 nm [Fig. 1(e)]. The liftoff process results in the second electrode pattern as shown in Fig. 1(f). The profiles of the patterned samples including PR were characterized by a scanning electron microscope (SEM, Philips XL30) and a profilometer (KLA-Tencor, Alpha-Step 500).

3. Results and discussion

Fig. 2 shows the ashing rate of PMMA in a vertical direction as a function of the reaction power and ashing time. As is shown in Fig. 2(a), the increase of the ashing rate was observed if the reaction power was raised regardless of PR type, and this phenomenon is similar to the results reported by K. Asano et al. [14]. However, the ashing rate of PMMA is higher than that of AZ1512: For example, the ashing rate of PMMA was approximately 4 nm/s at 200 W. On the other hand, the ashing rate of AZ1512 was approximately 3.3 nm/s even at high reaction power (300 W). Fig. 2(b) shows the PMMA thickness ashed in the vertical direction at various reaction power and time. We found that the reaction power is more important parameter to be controlled as compared to the reaction time. For example, the PMMA thickness ashed in the vertical direction increases more rapidly at 100 W as the reaction time increases. Since metal films will be deposited on the ashed patterns followed by the liftoff processing, the high aspect ratio of the PR patterns is desirable. Therefore, we need to control the reaction power very carefully. The data shown in Fig. 2(c) show the ashing rate of PMMA in the vertical and horizontal directions. The reaction power was fixed at 100 W for this case. We found in Fig. 2(c) that the rate of line width change over