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Design and fabrication of microcantilever probe integrated with microplasma reactor for maskless scanning plasma etching

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ABSTRACT

A novel maskless microplasma etching method based on parallel scanning probe microscopy is presented in this paper. The advantages of proposed etching system are high etching rate, high fidelity, simple-structure, and flexible to fabricate various material. The SiO_2 cantilever probe with microplasma reactor and nano-aperture at the hollow tip is designed and successfully fabricated with good quality. Experiment results show that the devices can discharge stably in SF_6 gas. The voltages–current (V–I) curves exhibit negative differential resistance of about 0.5 MΩ in a classical hollow cathode discharge mode. The pd scaling values (p and d are the SF_6 gas pressure and characteristic dimension of the microdischarge devices, respectively) for minimum ignition voltage are observed about 0.3–0.4 Pa m. Active F atom lines can be obviously found from the optical emission spectroscopy of microdischarge devices in SF_6 gas. A two-dimensional fluid model is used to simulate the dispersion distance and etching rate of silicon when the microplasmas are ejected through the nano-aperture. The experiment and simulation results verify the feasibility of the ongoing experiments of silicon maskless etching.

1. Introduction

Microplasmas or microdischarges typically refer to low temperature, non equilibrium plasmas confined to critical dimensions below about 1 mm. Due to many advantages such as small size, low power consumption, high electron density, high-pressure operation, and convenient portability, microplasmas open the door to a wide range of new applications such as light sources, displays, analytical chemistry, biomedicine, environmental remediation and material processing [1–3]. As a unique miniaturized plasma source, the applications of microplasmas in localized etching or three dimensional microfabrication of material have attracted more and more attention due to the merits of maskless patterning, high efficiency, convenience and cost savings [4–15]. Up to now, there are mainly two configurations reported for microplasma maskless etching. Some researchers have used microstructure electrode (MSE) discharges for maskless patterning of material. For example, Sankaran and Giapis [4,5] and Wilson and Gianchandani [6] used patterned MSE as stencil masks for silicon etching. Chai et al. [7] demonstrated a selective surface patterning by a copper clad polyimide MSE discharge. Due to the MSE discharge devices were patterned on the sample wafer to be etched, they cannot be used repeatedly with only simple patterns to transfer. Most other researchers have applied microplasma jet for localized maskless etching of material. For example, Yoshiki et al. developed a rf corona plasma jet for localized etching of photoresists [8], silicon wafers [9], polyimide films [10] and polyamide–imide (PAI) insulator film [11]. Ichiki et al. used a VHF (very-high-frequency-) driven atmospheric-pressure microplasma jet for ultrahigh-rate [12] and maskless 3-D etching [13] of silicon wafers. Ideno and Ichiki developed an atmospheric-pressure microplasma jet for maskless patterning of silicon [14] and silicon wafer slicing [15]. But in these applications of microplasma jets, so complicated RF matching network must be used, and parallel operation of multiple plasma-jets cannot be easily achieved due to not adopting MEMS processing to fabricate the device. Moreover, the main disadvantage of the above two configurations is the low etching resolution, usually from tens to hundreds micrometer, which is far from the requirements of high fidelity pattern transfer with micro or nano resolution.

So a novel maskless micro/nano plasma etching method based on parallel scanning probe microscopy is proposed by our group. As shown the schematic of etching system in Fig. 1, an inverted pyramidal microplasma reactor (or microdischarge device) is integrated into the hollow tip of a scanning probe. When applying dc excitation between the anode and cathode of the device in a definite gas pressure, microplasmas are generated and ejected through the nano-scaled aperture for maskless locally reactive ion etching. Etching different material can be achieved by selecting corresponding reactive gases, such as SF_6 for Si, CHF_3 for SiO_2/Si_3N_4, O_2 for

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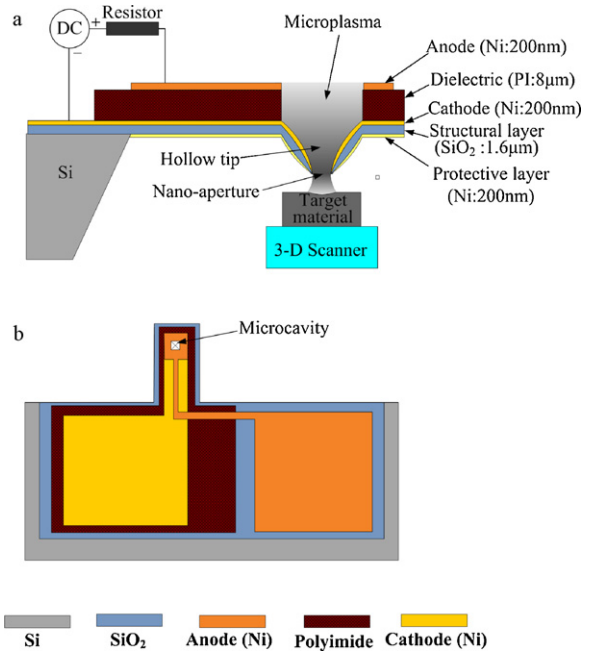

Fig. 1. Schematic diagram of maskless mircoplasma etching system based on parallel scanning probe microscopy. (a) The cross section and (b) the plane view of the etching system.

organic material. By combining the advantages of microplasmas and scanning probe fabrication technology, this etching system can realize maskless etching with high etching rate, sub-micro or nano scaled resolution and flexible to fabricate various material. Batch-produced economically and work in parallel efficiently is possible by adoption microfabrication technology.

In this paper, the SiO_2 cantilever probe integrated with inverted pyramidal microplasma reactor is designed and successfully fabricated by MEMS fabrication process. Electrical and optical characteristics of the microdischarge devices are tested in SF_6 gas at different pressure. Dispersion distance and etching rate of microplasma outside the nano-aperture are simulated using a two-dimensional fluid model.

2. Cantilever design

As shown in Fig. 1, the microplasma reactor is integrated into the hollow tip of SiO_2 cantilever. The microplasma reactor is metal–dielectric–metal sandwich structure with inverted, square pyramidal hollow cathodes. Metal nickel (Ni) is selected as the anode and cathode for its low sputtering yields, high melting and low cost. In order to ensure good electrical conductivity, the thickness of Ni films is designed as about 200 nm. Polyimide (PI305) is chosen as the material of dielectric film because it exhibits outstanding thermal, mechanical, electrical insulating, dielectric characteristics for microelectronic applications. Due to at least 200 V/μm dielectric breakdown strength of PI305, the thickness of the polyimide film is designed as 8 μm to ensure its breakdown voltage higher than 1000 V. The characteristic dimensions of the microcavities are designed as $(50\,\mu m)^2$ and $(100\,\mu m)^2$ square at the base in order to ensure stably generation of microplasma. A thermal oxidation SiO_2 film is chosen as the cantilever structural layer because thermal oxidation SiO_2 film is good elastic material and can act as self-stop layer during back-releasing of cantilever. The thickness of SiO_2 films is selected about 1.6 μm for the restriction of oxidation condition. Because generated microplasma must be extracted to the sample surface to realize maskless etching, a sub-micro or nano scaled aperture must be fabricated at the bottom of the hollow tip. In order to protect the hollow tip from etching of plasma, a 200-nm-thick Ni film is deposited as protective layer on the back side of the tip. The material properties of multilayer cantilever are shown in Table 1.

Table 1
Material properties of cantilever.

Material	Young's modulus (GPa)	Density (g/cm^3)	Ref.
Ni	190	8.9	[19]
Polyimide	3.4	1.45	[20]
SiO_2	87	2.2	[19]

In the work process of scanning maskless microplasma etching, the hollow tip at the cantilever end and the sample to be etched is non-contact. The spring constant and the first resonant frequency of the cantilever are two important design parameters. The spring constant depends on the required sensitivity, that is, the required minimum force derivative [16]. It should be low to yield a high sensitivity in the narrow detectable range. The first resonance frequency should be high to avoid vibrational excitation by external noise and to allow a high scan rate [16,17]. The lengths and widths of the cantilever are selected under the following conditions: (i) the spring constants are from 1 to 10 N m^{-1}, and (ii) the first resonance frequencies are from 10 to 100 Hz. For the multilayer cantilever, the spring constants and the resonance frequency are given by the following equations, respectively [16,18]

$$k = \frac{K_f}{l^3} \tag{1}$$

$$f = \left(\frac{1.875^2}{2\pi l^2}\right)\sqrt{\frac{K_f}{M_e}} \tag{2}$$

where k is the spring constant, f is the first resonance frequency, l is the effective length of the cantilever, and K_f and M_e are expressed by:

$$K_f = \sum_{i=1}^{n} c_i w_e h_i \left\{ \frac{h_i^2}{12} + \left[y_n - \left(\sum_{j=1}^{i} h_j - \frac{h_i}{2} \right) \right]^2 \right\} \tag{3}$$

$$M_e = w_e \sum_{i=1}^{n} \rho_i h_i \tag{4}$$

where n is the number of layers, h_i is the thickness of the ith layer, c_i and ρ_i are the Young's modulus and the density of the ith layer, respectively, w_e is the effective width of the layers and y_n is the depth to the plane of zero strain measured from the top of the beam (neutral plane). y_n is given by the following:

$$y_n = \frac{\sum_{i=1}^{n} c_i h_i \left(\sum_{j=1}^{i} h_j - (h_i/2)\right)}{\sum_{i=1}^{n} c_i h_i} \tag{5}$$

The dimension parameters of the multilayer cantilever used for calculation are shown in Table 2. The length and width of the cantilever are selected as 750 μm and 250 μm respectively. So the spring constant and the first resonance frequency are calculated as 5.98 N/m and 81 kHz, respectively.

3. Fabrication process

The fabrication process of the microcantilever is shown in Fig. 2. It mainly includes three parts, that is, microcavity formation, fabrication of microplasma reactor, cantilever releasing and nano-aperture formation.

The inverted pyramidal microcavity is formed by anisotropic wet etching. First, a Si wafer (p-type (1 0 0) orientation) is thermally