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Electrical properties of textured carbon film formed by pulsed laser annealing

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ABSTRACT

Previous works have showed that textured carbon film can be fabricated by applying suitable ion energy and substrate temperature. In this experiment, the effect of laser annealing on amorphous carbon films was studied. Atomic force microscopy shows the effect of laser irradiation on surface morphology of carbon film, and visible Raman spectroscopy shows that the G peak position shifted from 1540 cm^{-1} to 1600 cm^{-1}, and the increase in $I(D)/I(G)$ intensity ratio indicates the formation of more graphitic film at higher laser energy. High resolution transmission electron microscopy (HRTEM) shows the vertical alignment formation at suitable laser energy. Electrical measurement shows that the vertical aligned carbon films exhibit low resistance, ohmic current–voltage characteristics, which suggests that vertical aligned films formed by laser irradiation may be promising material for future nano-device interconnects.

1. Introduction

The use of the conventional copper interconnect for future CMOS backend process will be hindered by the significant increase in resistivity over its bulk value when the lateral dimensions are in the sub-100-nm regime [1]; this is mainly due to the electron scattering at grain boundaries and surface of narrower copper wires [2,3]. Carbon based materials, such as carbon nanotubes—(CNTs), and graphene are reported to have excellent electrical and thermal conductivity [4–6]. These carbon based structures do not suffer from the same problems as copper as they are less affected by electron migration because of the ballistic electron transport in those carbon materials [7,8]. However the growth of CNTs and graphene requires catalyst layer such as nickel, cobalt and copper with high temperature process (from 450 °C, and up to above 1000 °C) [9–12]; thus it is necessary to study new carbon based material with similar properties without the high fabrication complexity. Previous works have shown that another type of carbon material termed textured carbon can be fabricated by applying suitable ion energy and substrate temperature [13–16]. This type of carbon film is sp2 rich with their sp2 graphite-like planes ordered such that they are perpendicular with respect to the substrate. Because of the vast electron dislocation within the carbon layers, the electrical conductivity along the in-plane direction of graphite is high, and the through-film conductivity of the textured film would likewise be excellent [16]. Also because of the negative resistivity temperature coefficient [17], in contrast with the positive temperature coefficient of metal such as copper, the resistivity can be possibly lower under high current density condition. Therefore the textured carbon is considered as one of the promising materials to replace copper interconnects in CMOS nano-devices.

Our previous work shows that the textured carbon film can be formed by applying substrate bias and heating during the film growth, using a substrate bias of 600 V with the temperature of 600 °C, or even high temperature when applying a lower substrate bias [16]. However, the ultrashallow junction in current and future CMOS transistor will be more sensitive to the re-distribution of the implanted dopants, and which may occur at high temperature above 450 °C [18]. Therefore these high temperatures used to grow the textured carbon film are not compatible with the modern CMOS backend process. As such there is a need to find a lower temperature growth method for fabricating the textured carbon film.

One of the indentified methods of inducing texturing ex-situ of film growth is direct laser annealing. Annealing using laser has been widely used in CMOS process, such as silicon–carbon source/drain in MuGFET for enhanced dopant activation [19], nickel silicidation [20], and nanocrystalline Si formation [21]. It is reported that laser annealing can lead the formation of columnar nanocrystals in the amorphous silicon. More importantly, it is reported that pulse excimer laser can anneal the material with steep temperature slope and high selectivity; it can heat the annealing area of the material up to 2500 °C within a microsecond and remain other area and the underlayer of the material at room temperature [22]. Previous work by

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others using Raman analysis has shown that laser annealing can be used to change the bonding structure of a-C [23,24], and moreover, our own work has also shown that a-C can be converted to textured carbon at specific conditions, and the field emission property of the annealed carbon film can be enhanced using this way [25]. This approach is also very compatible with optical lithography as hard mask could be used to make direct patterns. Here in this work, we aim to study the laser annealing conversion of a-C to textured carbon. Through this work we will gain the exact conditions needed to change a-C to textured carbon using ex-situ laser excitation. A first look at the electrical properties of textured carbon will also be reported briefly here.

2. Experimental

The a-C films were prepared by the filtered cathodic vacuum arc technique (FCVA) on (100) n-type Si wafer at room temperature. Before film deposition, the Si wafer was firstly cleaned using acetone, followed by ultrasonic isopropanol (IPA) to remove the surface particles, and a titanium (Ti) layer with thickness of 50 nm was deposited using Denton Electron beam (E-Beam) evaporation on the Si substrate, which was used as the bottom electrode for electrical measurement later on. The cathode used was the 99.999% pure graphite rod. The deposition was carried out at a vacuum in the 10^{-6} Torr range, at room temperature. Negative DC substrate bias of 300 V was applied to the substrate during the deposition to control the initial property and microstructure of the a-C film. The a-C film was deposited on the Ti with 3 mm periodic spacing, which with the Ti area being covered using thermal tape on the probing area. After the film deposition, it was cut into small piece with dimension of 3 mm × 6 mm (carbon film is 3 mm × 3 mm in dimension, same as the spot size of the laser used in the annealing step). The thickness of deposited C films was measured to be 100 nm using Tencor P10 surface profiler meter; no delamination and peeling-off area was found. 248 nm KrF excimer-laser with pulse duration of 23 nm was used to anneal the samples in ambient condition. The spatial energy distribution of the laser pulse has a uniform near flat-top energy profile [26]. The samples were annealed by just one single pulse.

Tapping mode atomic force microscopy (AFM) was firstly used to measure the surface morphology before and after laser annealing. For structural analysis, two systems were used. The first was a Renishaw visible Raman spectroscopy (50 mW 514 nm Ar^{+} ion laser) that was used to obtain the information concerning the structure transitions within the irradiated areas. The Raman spectra were fitted using a Lorentzian line shape for the D band and a Breit–Wigner–Fano (BWF) line shape for the G band. The second was a JEM 2010 transmission electron microscopy (TEM) operated at an acceleration voltage of 200 kV.

To perform the IV characterization measurement, a two point probing method was used. The test structure was prepared in a Ti—C—Ti structure illustrated in Fig. 1. The top and bottom electrode was 50 nm, and the diameter of top Ti electrode was 500 μm. A cascade 200-mm probe station with a Keithley 4200 serious semiconductor measurement system was used to perform the DC IV characteristic measurement, with a volt step of 0.1 V.

3. Results and discussion

3.1. Surface morphology evolution upon laser annealing

Fig. 2 shows the surface root mean square (RMS) roughness for the sample both pre and post annealed using different laser energy densities, and insets (a) and (b) show the 3D AFM image of as-deposited C film and C film annealed using 665 mJ/cm^2. The surface of the as-deposited film is smooth which is consistent with typical a-C deposition using the FCVA technique [27]. It is observed that the surface RMS roughness increased when the laser energy density is beyond 400 mJ/cm^2. One reason for this is because of the surface damage due to laser irradiation, simulation and experimental works have shown that heating effect can be generated by laser irradiation, a single pulse KrF excimer laser with laser energy density of 80 mJ/cm^{2}can heat carbon film upon 300 °C, and the damage temperature of carbon film surface is about 785 °C [28]. It is expected that the heating effect generated by laser with 400 mJ/cm^2 is more than 785 °C. [24,28]. Another reason for the surface RMS' increasing is probably due to the stress relaxation caused by laser annealing. The heating effect of laser annealing can cause the sp3 to sp2 conversion, and the formation of the sp2 clusters [25,29]. The annealed film with less sp3 content will have lower stress with respect to the as deposited film [30]. Lifshitz's results [31] suggest that film with high sp2 content and larger sp2 cluster size tends to have rougher surface.

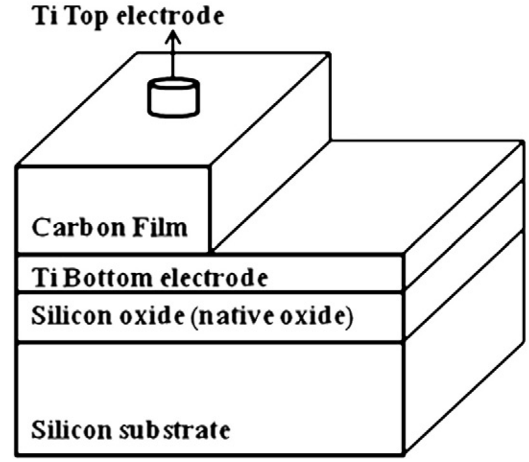

Fig. 1. Schematic of the Ti—C—Ti structure used to perform electrical measurement. (Note: this figure is used for illustration only; the size is not proportional to the real structure).

3.2. Microstructure structure evolution upon laser annealing

Fig. 3(a) shows the Raman spectra for the sample both pre and post annealed using different laser energy densities. The as-deposited a-C film using the substrate bias of 300 V has been reported by others to be amorphous [32], and that its Raman spectra can be

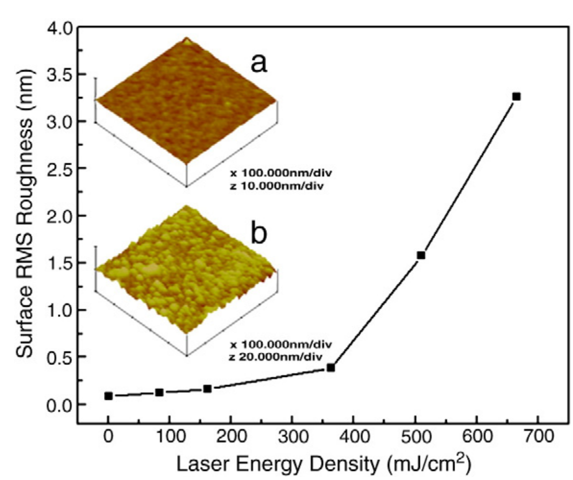

Fig. 2. Surface RMS roughness with respect to the change of laser energy density used in laser annealing. Inset (a) AFM image of as-deposited C film and inset (b) C film annealed using laser energy density of 665 mJ/cm^2. (It shows that the surface of the C film will have a significant increase annealed using high laser energy density.)