

Properties of Al contacts to Si surface exposed in the course of plasma etching of previously grown nanocrystalline c-BN film

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Abstract—Properties of Al electric contacts to Si(p) surface exposed to fluorine-based plasma etching of nanocrystalline cubic boron nitride (c-BN) film grown previously were studied and compared to the properties of Al contacts fabricated on pristine or dry etched surface of Si(p) wafers. In addition, a part of the investigated samples was annealed in nitrogen atmosphere at the temperature of 673 K. Analysis of contact properties is based on current-voltage (I - V) measurements of the produced Al-Si structures. The presented investigations were performed in order to evaluate the efficiency of the applied plasma etching method of nanocrystalline c-BN from the viewpoint of its influence on the properties of metal contacts formed subsequently and thus on the performance of electronic devices involving the use of boron nitride.

Keywords—cubic boron nitride, plasma etching, electric contacts.

1. Introduction

Cubic boron nitride (c-BN) owing to its unique properties, such as wide bandgap, good thermal conductivity, high thermal stability and chemical resistance, is a promising material for numerous applications. These cover such areas as high-temperature and high-power electronics, UV (included deep UV) detection and light emitting devices or structures intended to work in chemically harsh environments [1–3].

Fabrication of metal-insulator-semiconductor (MIS) structures with boron nitride layer playing the role of an insulator is quite easy and offers a very useful tool for electronic characterization of a dielectric film (BN in this case) [4, 5]. MIS systems also form very convenient testing ground for verification of various processing technologies of the investigated insulating material, e.g., etching [5–7] or fabrication of metal contacts [8]. However, elaboration of the complete technological process leading to the fabrication of an advanced device making use of BN (e.g., MIS field-effect-transistor (MISFET), where boron nitride film acts as a gate insulator) is a much more demanding task. Among other things it requires the development of a selective etching technique of BN film, which allows desired features (gate area in this case) to be patterned on its surface. Due to the aforementioned chemical resistance, boron nitride

is difficult to be removed by means of wet etching, typically used in electronics. Much more promising results are brought by experiments with dry plasma selective etching of BN [5–7]. However, in order to determine the real usability of the applied method, it is necessary not only to investigate the efficiency of material removal or selectivity of such a process, but also to examine the influence of the process on the characteristics of the final device. Plasma is an aggressive environment and comes into interaction with the surface (e.g., substrate) being exposed, undoubtedly affecting its state, even if the etch stop moment is selected correctly. In this work we have studied the properties of Al contacts to Si surface, which were formed after removal of nanocrystalline c-BN film grown previously. Any practical application requires the availability of contact fabrication method ensuring the contacts exhibit desired properties. This may also include the knowledge of how to bring such contacts into the right state if they do not possess the required parameters initially (immediately after formation). In the present study our goal was to obtain ohmic contacts to plasma exposed Si surface, as such terminals are necessary for, e.g., source and drain regions of the planned MISFET structures. Ohmic character is here considered primarily in the sense of small contact resistance with respect to the resistance of the substrate or device, rather than in terms of strict linearity of the observed current-voltage curves [9].

2. Experimental details

Nanocrystalline, 60–80 nm c-BN films were produced on p-type Si ($\langle 100 \rangle$, $\rho = 6\text{--}8 \Omega\text{cm}$) substrates using reactive pulse plasma (RPP) assisted CVD method [10]. Then BN layers were dry etched in fluorine based r.f. (13.56 MHz) plasma (PLASMALAB OXFORD 80+ station). Selectivity of etching was achieved by applying aluminum metallization as a mask. Etching process parameters are presented in Table 1. The results of etching were verified by ellipsometric measurements (GAERTNER 117, $\lambda = 632.8 \text{ nm}$) as well as scanning electron microscopy (SEM). Subsequently, Al contacts were vacuum evaporated on such surfaces. In order to determine the potential influence of BN removal on electrical properties of Al contacts formed on

plasma-exposed Si surface, in parallel a comparative set of Al contacts was fabricated on pristine Si wafers (of the same type as above) that were not covered with boron nitride. Another set of contacts was evaporated on Si substrates that were initially plasma pre-etched (under the same conditions as shown in Table 1 except shorter – 0.5 min – process time). This step was intended to simulate the effect of the final stage of BN plasma etching of Si surface, when it becomes directly exposed to the plasma environment. Finally, a part of the obtained structures of all types was annealed at the temperature of 673 K for 30 min in nitrogen atmosphere. All wafers had Al backside contacts as well.

Table 1

Process parameters of nanocrystalline c-BN film etching

Parameters	Values
Gas mixture	CF ₄ + Ar
Flow rates of gas mixture components [ml/min]; CF ₄ to Ar	30 to 10
Power [W]	100
Pressure [mTr]	40
Etching time [min]	3 (0.5*)
* In the case of pristine Si surface pre-etching.	

Electrical properties of Al contacts were investigated by means of automatic current-voltage (*I-V*) measurements with Keithley SMU 238 within the range ± 10 V with the current monitored every 0.1 V.

3. Results and discussion

Since ellipsometrical measurements of the thickness of nanocrystalline c-BN layers performed after completing

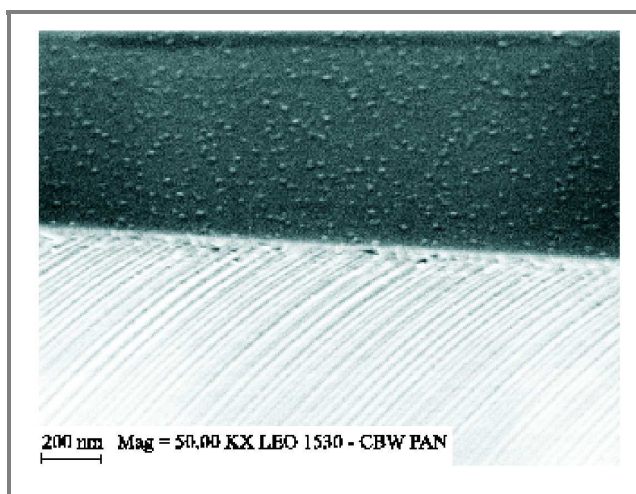


Fig. 1. SEM image of a fractured Si substrate showing the surface of the wafer exposed to plasma in the course of plasma etching of a nanocrystalline c-BN film grown previously.

the etching process gave ambiguous results (some readouts suggested 2.5–3 nm thick residue of boron nitride film), in addition SEM images of sample surface were obtained (see Figs. 1 and 2). They seem to indicate that the boron nitride layer was successfully removed, except some isolated islands of unetched material (separated on the average by a distance of 100 nm one from another), most likely composed of chemically resistant compounds like BC_x, BCN, C_xN_y, etc. (Fig. 1). Their local character suggests that they should have no significant influence on Al contact properties. However, even if BN layer residuum formed a continuous film, it should not be a problem since in the case of such a thin film quantum tunneling effects start playing a crucial role in carrier transport and thus that kind of interface cannot be a barrier for current flow. At the same time trenching effects were observed around the edges of Al metallization used as an etching mask, as well as erosion in the case of a particular edge (Fig. 2). These are phenomena characteristic of physical

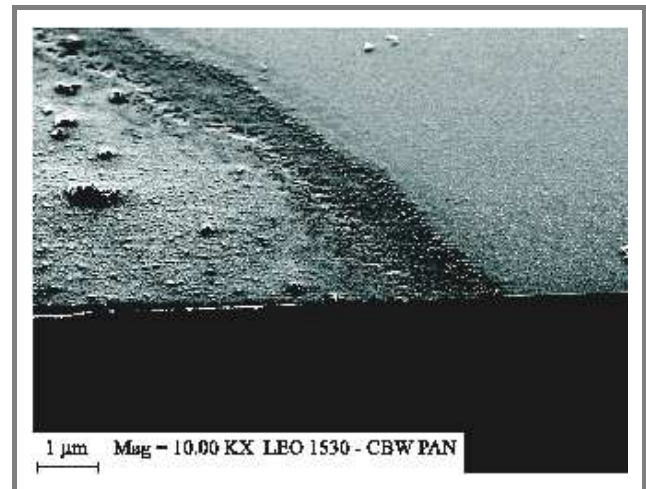


Fig. 2. SEM image of a fractured Si substrate with Al masking metallization after plasma etching process.

sputtering, which indicates most likely that the composition of reactant gases should be changed in favor of the component responsible for chemical etching (in our case CF₄ at the expense of Ar). This observation is supported by our previous studies concerning dry plasma etching of gallium nitride (GaN) by means of the same method, where improvement was observed if the content of chemically etching component was increased in the reactant gas mixture [11].

The results of *I-V* measurements of different sets of Al/Si structures are shown in Figs. 3–8.

Figure 3 presents current-voltage curves observed for Al contacts evaporated onto Si surface exposed to plasma during c-BN layer etching. As it can be seen, these characteristics are strongly asymmetric. However, the situation changes dramatically after annealing (673 K, N₂ atmosphere), as characteristics become symmetrical (Fig. 4). Now, if such curves are compared to the corresponding

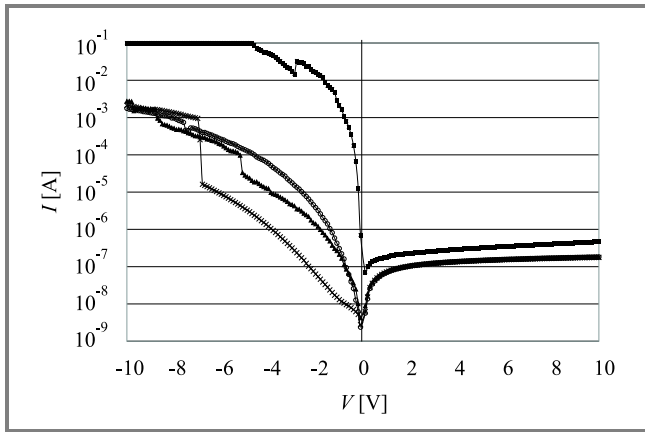


Fig. 3. I - V characteristics of Al contacts evaporated onto Si surface exposed to plasma during plasma etching of a nanocrystalline c-BN film grown previously.

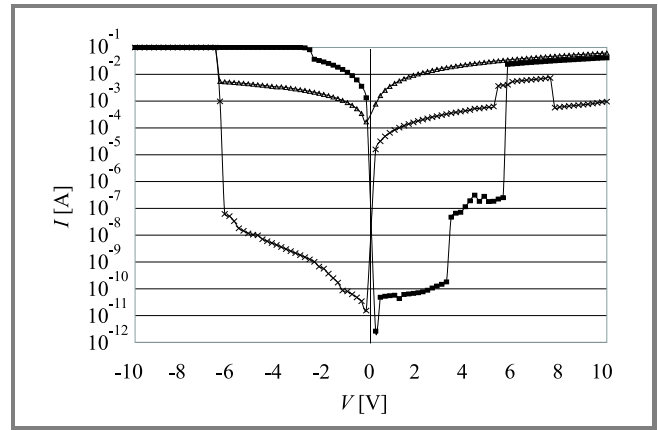


Fig. 6. I - V characteristics of Al contacts evaporated on pristine and shortly plasma-etched Si surface – results of contact annealing at 673 K in N_2 atmosphere.

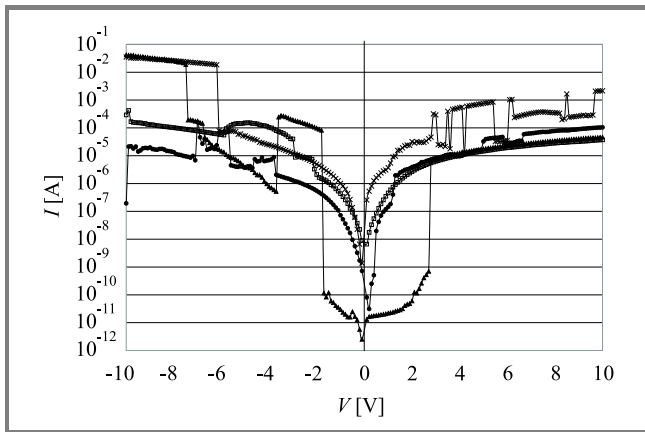


Fig. 4. I - V characteristics of Al contacts evaporated onto Si surface exposed to plasma during plasma etching of nanocrystalline c-BN film grown previously – results of contact annealing at 673 K in N_2 atmosphere.

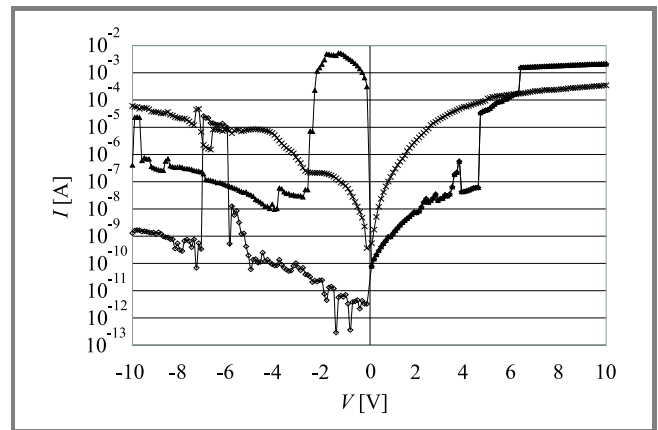


Fig. 7. I - V characteristics of Al contacts evaporated on pristine Si surface that was not subject to pre-evaporation plasma etching.

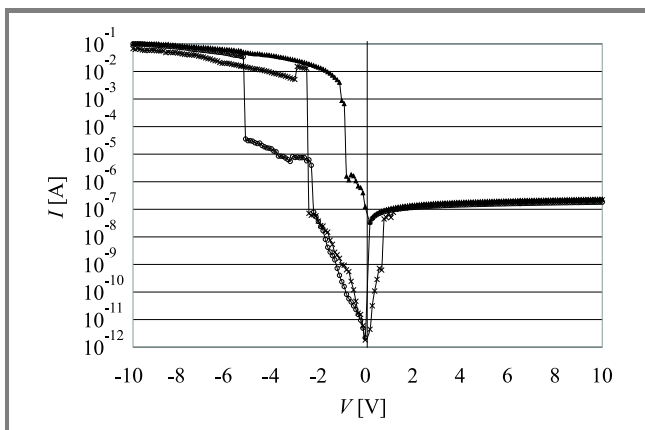


Fig. 5. I - V characteristics of Al contacts evaporated on pristine and briefly plasma etched Si surface.

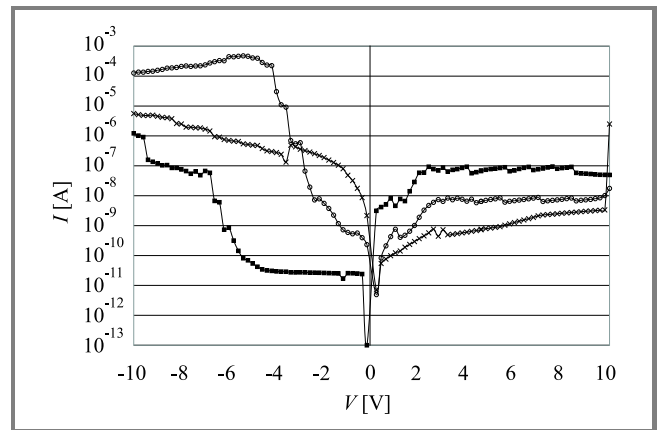


Fig. 8. I - V characteristics of Al contacts evaporated on pristine Si surface that was not subject to pre-evaporation plasma etching – results of contact annealing at 673 K in N_2 atmosphere.

characteristics obtained for contacts evaporated on pristine and plasma pre-etched Si substrates, it becomes evident that one has to deal with a similar trend. It is clear that non-annealed electrodes act as rectifiers (Fig. 5) but after annealing (Fig. 6), the characteristics of both structure types become symmetrical. Slightly lower current level in the case of contacts grown on Si surface truly exposed to plasma in the course of BN etching seems to be the obvious result of the remaining BN residues and other post-etching contaminants which effectively increase the contact resistivity. The similarity of the I - V characteristics of both sample sets seems also to be an indirect proof that plasma etching was successful since otherwise the obtained curves might be quite different.

Figures 7 and 8 present behavior of analogous I - V curves, obtained for Al contacts produced on pristine Si surfaces that were not exposed to plasma prior to Al evaporation. As it can be seen, they perform much worse, especially as far as their resistivity is concerned (definitely lower current levels). This seems to be in accordance with the well-known fact that better ohmic contacts are achieved if semiconductor surface is defected (resulting in the formation of high density efficient recombination centers causing significant decrease in the contact resistance, as well as generally promoting better metal adherence to the semiconductor) [9, 12]. Therefore annealing (Fig. 8) had apparently no influence on I - V curves observed for this set of samples.

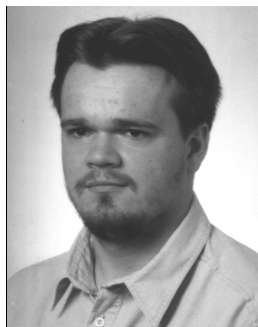
4. Conclusions

The presented investigations show that fluorine based r.f. plasma etching of nanocrystalline c-BN films is an efficient way to selectively remove boron nitride and to pattern BN layers for the purposes of application in microelectronics (in this case – obtaining of gate dielectric in MISFET structures). A c-BN film may be removed from any unmasked substrate region areas. Studies of the properties of Al contacts to Si substrate regions exposed to plasma in the course of BN-layer etching prior to evaporation (and comparative studies of analogous structures evaporated on silicon surfaces never covered with BN) demonstrate the possibility of fabricating contacts that meet requirements for electrical ohmic terminals for semiconductor devices. Ohmic character means here rather a low contact resistance compared with the resistance of substrate or device and not essentially the linearity of its I - V characteristics. In other words, plasma processing does not affect the characteristics of Al electrodes that are to be formed later on in a negative sense.

Moreover, it has an even beneficial influence because of a certain level of surface damage that improves metal adhesion and introduces recombination centers decreasing the resistance of the metal-semiconductor system. As expected, annealing plays a substantial role in improvement of contacts fabricated in this way.

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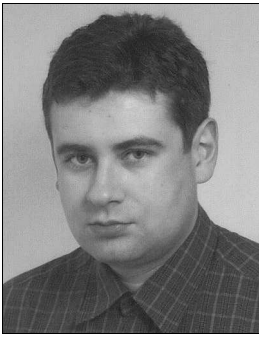


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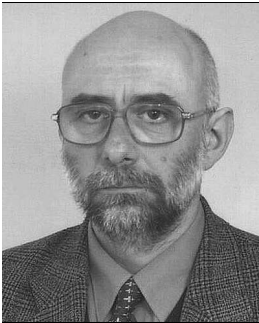
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