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Diamond merged diode

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Abstract

To obtain high blocking voltages and low forward losses in power diode structures, a Schottky contact can be merged with a MIS contact or a pn-junction. In this configuration, the Schottky contact is responsible for a low forward threshold voltage and the MIS or pn-junction for a low reverse leakage current and a high breakdown voltage. In this study, a diamond merged diode structure has been fabricated and evaluated, containing simultaneously an Al or W:Si-Schottky contact and a boron/nitrogen pn-junction. The IV characteristics show a low forward barrier of 1.5 eV, a current rectification ratio of 10^9 at R.T., and a reverse breakdown at 2.5 MV/cm. Rectification has been obtained up to 1000 °C (in vacuum).

Keywords: Diamond; Merged diode

1. Introduction

High voltage high power switching devices must combine two contradicting properties, namely high blocking voltages and low forward losses. For small forward losses, a small threshold voltage is needed, implying a low barrier metal semiconductor junction. At reverse bias however, the Schottky barrier lowering effect will increase current leakage and reduce breakdown voltage. To obtain ideal reverse characteristics, a buried pn-junction should be employed, which in turn exhibits a high forward threshold voltage.

The combination of a Schottky contact with a pn-junction would enable to benefit from both; low forward losses and high breakdown strength, if the low Schottky barrier is shielded at high reverse bias. In the merged diode concept, shielding is provided by the lateral field of a pn-junction [1,2]. In the superjunction concept, an MIS junction is used to reduce lateral field spikes [3]. Thus, in these heterogeneous junction concepts Schottky contact areas are surrounded by high barrier contact areas to eliminate fringing effects. Merged diode structures in SiC usually use ion implantation to define either highly doped pn-junction or semi-insulating regions [4]. Thus, the Schottky contacts are placed above these junction profiles, resulting in a vertically confined current flow through the Schottky diode interface at forward direction and a vertical field profile in reverse direction.

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2. Diamond diode concept

To realize such a merged diode concept in diamond only few technologically relevant building blocks are available. These are active layer doping by boron in-situ during epitaxy, the

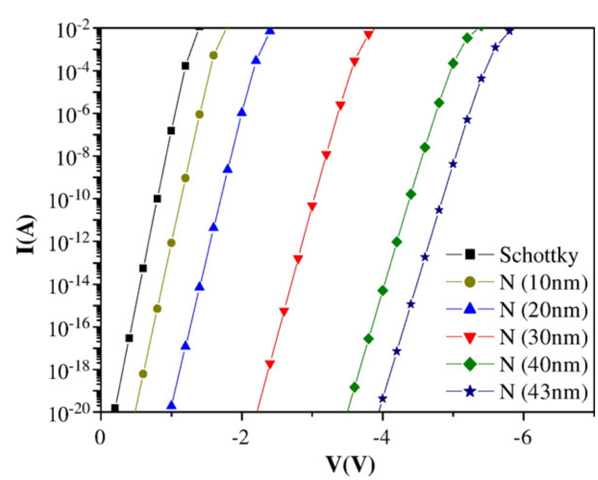

Fig. 1. Influence of the thickness of the nitrogen (deep donor) doped layer on the diode threshold voltage compared to a Schottky contact as obtained by device simulation (Silvaco). With increasing thickness of the nitrogen doped layer, the slope changes (n factor increases) and above a certain thickness the current flow stops entirely and the characteristics are MIS-like.

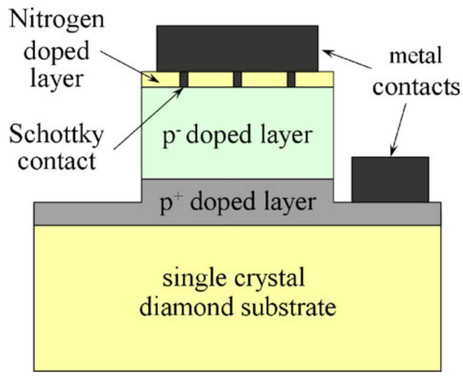

Fig. 2. Cross-section of the merged diamond diode structure. The small area Schottky contacts are merged with a vertical pn-junction.

Schottky contact on the oxygen terminated surface with a barrier height of approx. 1.7 eV, and the nitrogen/boron pn-junction with a built-in potential of 3.8 eV. In the diode structure, the Schottky metal will be deposited across the entire surface and will therefore also serve as contact metal for the pn-junction. Due to the extremely deep nitrogen donor level, the pn-junction may represent a lossy dielectric junction similar to a MIS contact depending on the thickness of the nitrogen doped layer. For a nitrogen doped layer within tunneling thickness, the barrier will still be determined by the Schottky barrier potential. With increased thickness of the layer, the contact will become that of a camel diode with still low series resistance. Only at extended thickness will the nitrogen-doped layer act as lossy dielectric resulting in MIS-like characteristics. Therefore, to gain advantage of the full pn-junction barrier potential, a certain thickness of the nitrogen-doped layer is needed. Simulation (Fig. 1) indicates that this thickness is in the order of 30 nm.

In the present approach, a merged diode structure with small size Schottky contact areas embedded into a surface-near nitrogen/boron junction has been realized. It will therefore combine a 1.7 eV forward barrier IV characteristics with a reverse pn-junction characteristics.

3. Experimental

Commercially available single crystal type 1b substrates have been used for the growth of the vertical diode structure by MPCVD. A pre-growth H-plasma surface treatment has resulted in a surface roughness of 0.5 nm rms. This was followed by a p^+ boron-doped contact layer, consisting of a sequence of multiple boron delta-doped layers to reduce the stress in this layer generated by the high boron concentration needed for full activation. The delta doping process employed is similar to the one described in [5]. The layer consists of 5 delta-doped profiles with a total thickness of 30 nm. The growth parameters were: $p=2$ kPa, $T=750$ °C, $P=700$ W, hydrogen flow of 200 sccm, and a specific sequence of pulsed growth steps employing different methane concentrations and a boron rod, which is immersed into the plasma for a short period of time. This was followed by the growth of a 100 nm thick intrinsic layer in a second MPCVD system not contaminated by boron. On top of this active (nominally undoped) layer, a thin nitrogen doped cap layer of approx. 10 nm thickness has been grown.

The diode structure is schematically shown in Fig. 2. Circular diode patterns, with diameters between 20 and 160 μm, have been mesa etched by O_2/Ar dry etching to obtain vertical current flow. The etching has been terminated on the p^+-doped layer, which was used for ohmic contacts. The pn-junction has been tested employing Al metal pads. In the next step, the Al-layer was removed and the surface patterned by e-beam lithography to obtain small sized Schottky contact areas as illustrated in Fig. 3. The diameter of the Schottky contact spots was approx. 0.6 μm. The overall Schottky contact area was approx. 10^{-2} of the total diode surface. The Schottky contact itself was then realized by dry etching of the e-beam openings in a resist by O_2/Ar-plasma through the nitrogen doped top layer. Finally the entire diode surface was covered by the Schottky metallization, which was Al or in the case of high temperature measurements W:Si/Ti/Au [6].

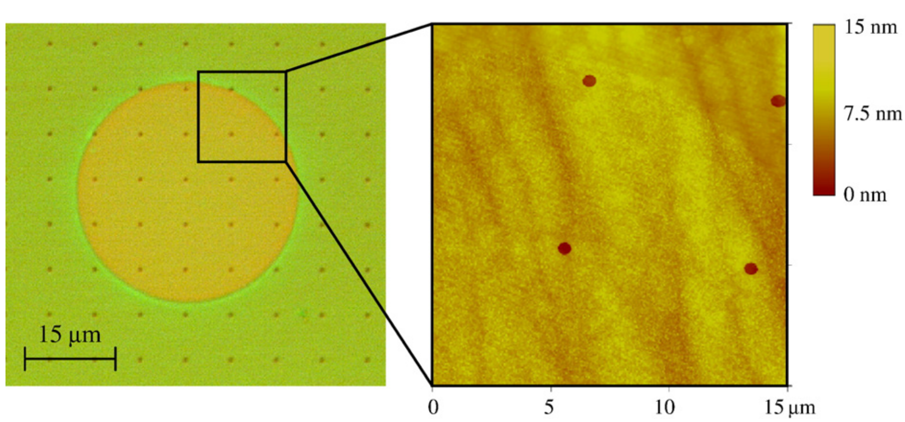

Fig. 3. Pattern generated by E-beam lithography for the definition of the Schottky contact areas on a circular diode surface with 40 μm diameter. The left image shows a micrograph of an etched diode structure with a regular distribution of small Schottky contact areas with 0.6 μm diameter. The right AFM image is a scan of the surface topology after etching of the Schottky contact areas.