Scripta Materialia 159 (2019) 58–61

Contents lists available at ScienceDirect

Scripta Materialia

journal homepage: www.elsevier.com/locate/scriptamat

Room-temperature direct bonding of diamond and Al

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ARTICLE INFO

Article history:
Received 11 June 2018
Received in revised form 30 August 2018
Accepted 12 September 2018
Available online xxxx

Keywords:
Diamond/Al direct bonding
Surface activated bonding
Bonding interface
Amorphous layer

ABSTRACT

Direct bonding of diamond and Al is achieved by surface activated bonding at room temperature. The interfacial structures of the diamond/Al bonding interface with annealing at different temperatures are investigated under in-situ annealing in a transmission electron microscope (TEM). An amorphous layer with a thickness of 4 ± 0.5 nm is formed at the bonding interface without annealing, the thickness of the amorphous layer decreases with increasing annealing temperature, the amorphous layer vanished after annealing at 600 °C. No structural defects are observed at the bonding interface with annealing at different temperatures.

Electronic semiconductor devices such as metal oxide semiconductor field effect transistor (MOSFET), bipolar junction transistor (BJT), insulated gate bipolar transistor (IGBT), high electron mobility transistor (HEMT) have been extensively used in home electronics, telecommunication, transport, electric grid and numerous other applications. The high operating power density in such devices commonly produces an increase in temperature near the active device region, which would degrade device performance and reliability [1–3]. Therefore, the suppression of the temperature rise is particularly important to increase the operational power density.

Diamond has the highest thermal conductivity among materials and is an ideal material to suppress the rise in the device temperature when integrated with electronic devices. The integration of GaN-based devices and diamond by direct growth and wafer bonding has been recently demonstrated, resulting in improved thermal management and three-fold increase in areal power density [4,5]. Devices have been commonly directly mounted onto the heat sink by solder bonding [6] or hydrophilic bonding [7]. For any device, an effective thermal boundary resistance exists between the device and the heat sink, which is a significant thermal barrier for heat transfer from the device to the heat sink. Because the thermal conductivity of the solder materials such as AgSn and AuSn is very low in comparison with that of diamond.

In this work, we directly bonded polycrystalline diamond substrate to aluminum (Al) by surface activated bonding (SAB) at room temperature and investigated the structural properties of the bonding interface by transmission electron microscopy (TEM) and energy dispersive X-ray spectroscopy (EDX). In situ observation of microscopic structural change in a TEM of the bonding interface at various annealing temperatures was carried out within a filament type heating TEM holder. During bonding process, the surfaces of the bonding materials were activated by the irradiation of Ar fast atom beam. We

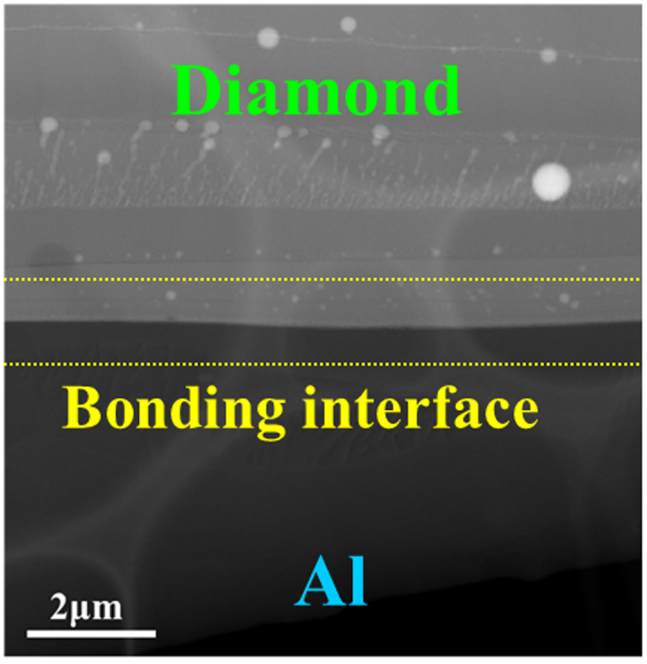

Fig. 1. A low magnification cross-sectional TEM image of the diamond/Al bonding interface without annealing. Note that the observed white spherical objects were Ga contaminations caused during TEM sample fabrication by focused ion beam (FIB).

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https://doi.org/10.1016/j.scriptamat.2018.09.016
1359-6462/

consequently investigated the chemical bonding states of polycrystalline diamond surface without and with Ar irradiation, and with annealing at 600 °C after Ar irradiation, and as well as the bonding interface with annealing at 600 °C by X-ray photoemission spectroscopy (XPS).

Commercial polycrystalline diamond and Al were used for our bonding experiments. The size of the diamond and Al substrates are 10 mm × 10 mm × 0.25 mm and 20 mm × 15 mm × 0.25 mm, respectively. Prior to the bonding, the surface of the diamond substrates was polished by chemical mechanical polishing. The averaged roughness of the polished diamond surface and Al substrate surface was measured to be 0.32 and 70 nm, respectively, by using atomic force microscopy (AFM). Al and the polished diamond substrates were cleaned with acetone and ethanol in an ultrasonic bath for 300 s, dried under N_2, and then set in the vacuum chamber of bonding facility. The background vacuum pressure was kept at 5.0×10^{-7} Pa. The surfaces of the diamond and Al were simultaneously activated by the Ar fast atom beams irradiation with a power of 1.5 kV and 1.5 mA for 180 s. After surface activation, they were bonded to each other at room temperature by applying a pressure of 10 GPa for 60 s, i.e. using surface activated bonding (SAB) with more details described in Ref. [8–10]. The structure of the diamond/Al bonding interface was investigated using a TEM (JEM-2200FS) equipped with EDS. The microstructural change of the bonding interface with annealing at different temperatures were investigated by in-situ TEM observation at room temperature under a high vacuum (~1×10^{-5} Pa). The chemical bonding structures of diamond without and with Ar irradiation, and with Ar irradiation and annealing at 600 °C were characterized using XPS (ESCA-3400) with a monochromatic Mg *Kα* x-ray radiation source.

Fig. 1 shows a low magnification TEM image of the cross section of the diamond/Si bonding interface without annealing. A straight line could be clearly recognized at the center of the figure, which corresponds to the bonding interface between diamond and Al. We found that most of the bonding interface is smooth and free of micro-voids, and direct bonding of diamond and Al in the micro scale were achieved.

The cross-sectional TEM images of the diamond/Al bonding interface without and with annealing at 200, 400, and 600 °C are shown in Fig. 2 (a), (b), (c), and (d), respectively. As shown in Fig. 2(a), a transition layer with a thickness of 4 ± 0.5 nm was formed at the bonding interface. The thickness of the transition layer was reduced from 4 ± 0.5 nm to 3 ± 0.5 nm after annealing at 200 °C. Furthermore, when the annealing temperature increased to 400 °C, the thickness of the transition layer was decreased to 2 nm. Finally, the transition layer disappeared after annealing at 600 °C. The continuous lattice fringes across the interface at the bonding interface suggests that a well-defined interface was formed. The thickness of the transition layer is therefore highly depended on the post-annealing temperature, which decreased with

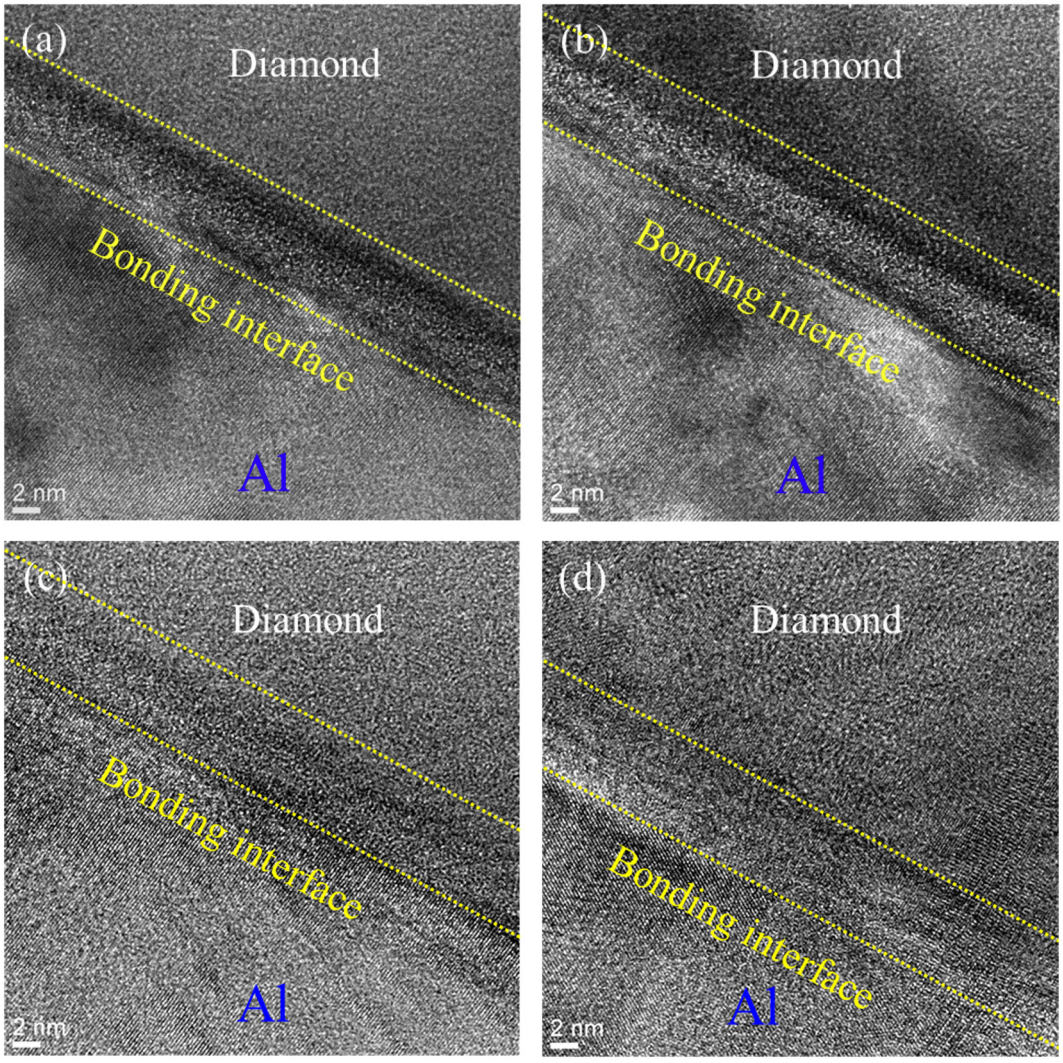

Fig. 2. High magnification cross-sectional TEM images of the diamond/Al bonding interface without (a) and with annealing at 200 (b), 400 (c), 600 °C (d). The bonding interface was annealed by In-situ annealing TEM holder under high vacuum.