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Effect of sliding velocity on tribochemical removal of gallium arsenide surface

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ABSTRACT

During machining and polishing of GaAs, surface material removal has become an issue of much concern. By using an atomic force microscope and a spherical SiO_2 tip, the nanoscratch tests were conducted on GaAs(100) surface under various sliding velocities. The depth of the scratches increases with the decrease in the sliding velocity. High-resolution transmission electron microscope (HRTEM) detection shows that no damage, such as lattice distortion, dislocation and crystal slipping, can be found from the cross-section of the scratches created at various sliding velocities. Further analysis suggests that the material removal on GaAs surface may be attributed to the dynamical formation and break of interfacial chemical bonds. Compared to low-speed sliding, high-speed sliding will induce a much larger rate of material removal of GaAs surface. Therefore, if the SiO_2 particles are used in the polishing of GaAs surface, high polishing speed can bring high rate of tribochemical removal without damage to the surface matrix of GaAs.

1. Introduction

Due to its direct bandgap and high electron mobility, gallium arsenide (GaAs) was widely used in the devices from macroscale to nanoscale for illumination, photoelectric detection, conversion of solar energy and so on [1–7]. To satisfy the increasing requirements of high-quality products, mechanical processing of GaAs is needed, where the tribological performance has become an issue of much concern [8]. Furthermore, during the contact and movement of component surface at micro/nanoscale, the device lifetime is much restricted due to nano-tribological problems such as high friction and serious wear [9,10]. Therefore, complete investigation on the surface wear and material removal of GaAs can not only help us to understand the wear mechanism of GaAs at the nanoscale, but also provide meaningful insight in surface polishing of GaAs wafers [11–13].

During the past years, the tribological study of GaAs was mainly focused on the mechanical wear by diamond tip [14–19]. Michler et al. [14] observed in situ the microwear of GaAs wafer during microscratching by a diamond tip. They found that the cracks on GaAs were generated on the side and in front of the tip, while the debris via interaction of the chevron-shaped cracks was formed in front and on the rear side of the tip. Based on a nano-scratching tester, the evolution of plastic deformation and cracking behavior was investigated [15]. The dislocations were detected prior to the formation of median cracks and surface radial cracks. Following that, lateral cracks, radial cracks and large chips were observed in sequence with the increase in the applied normal load. It was also stated that twinning and dislocations of crystal matrix usually took place in an indentation process, whereas slip bands and perfect dislocations were observed after scratching [16,17]. Such a different behavior was explained via the strain rate, which in scratching is 100 times greater than that in indentation. By scratching at 4 mN using a conical diamond tip with the curvature radius of 1 μm, the lattice bending was observed on GaAs, which was ascribed mainly to the residual stress [18]. Moreover, the measured hardness and elastic modulus of GaAs decreased with the increase in the indentation depth, which may have much impact on the tribological performances towards different test depths [19].

Although the mechanical deformation in GaAs was extensively studied, the tribochemical interaction was far from understood. In fact, the tribochemical interaction was found to play a significant role in nanoscratch tests [20]. It is noted that the surface material on GaAs can be removed by tribochemical interaction at a low contact pressure before the yield of GaAs. For the processing of GaAs surface, the efficiency of material removal is an issue of much concern, which is dependent strongly on the machining speed [12]. Study on sliding velocity-dependent material removal is important to understand the removal mechanism and optimize the process for surface planarization.

In the present study, the effect of sliding velocity on tribochemical removal of gallium arsenide surface was investigated. A series of

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scratch tests were conducted on GaAs(100) surface by an atomic force microscope (AFM) at various sliding velocities. Based on the high-resolution transmission electron microscope (HRTEM) detection on the cross section of scratched area, the removal mechanism was discussed.

2. Materials and methods

The n-type GaAs(100) wafer doped with Si, purchased from Hefei Kejing Materials Technology Co., Ltd. in China, was used in this study. By using an AFM (E-sweep, Hitachi, Japan), the surface root-mean-square (RMS) roughness of the GaAs wafer was measured as less than 0.5 nm over an area of 2 μm × 2 μm. Before the test, the GaAs wafer was cut into pieces of about 1 mm × 1 mm, and then ultrasonically washed in acetone, alcohol and deionized water in turn to remove the surface contaminations.

The nanoscratch test on GaAs (100) surface was performed by an AFM with an ambient chamber. A spherical SiO_2 tip with a nominal radius R of 1.25 μm (Novascan Technologies, USA) was used. After removal of the sphere curvature, the surface roughness was calculated as ~0.4 nm over a 250 nm × 250 nm area. To obtain a stable tip, the tip was pre-scanned for 500 cycles on GaAs surface at a load of 2 μN and sliding speed of 10 μm/s. The applied normal load for the present study was 2 μN, and the sliding velocity ranged between 0.1 μm/s and 1000 μm/s. The number of scratching cycles is 100 for each scratch. The atmosphere temperature was ~26 °C. The relative humidity (RH) inside the chamber was measured online by a hygrometer. To control the RH at a target value, the chamber is firstly vacuumized by a pump, and then filled with the mixture of dry air and humid air. During the tests, the RH inside the chamber was maintained at 52 ± 2%. To obtain reliable data, at least three scratch tests were performed at each sliding speed. After scratching under various sliding velocities, the topography of the scratched area was scanned in situ by a sharp Si_3N_4 tip with $R \approx 20$ nm (MSCT, Bruker Corporation, USA).

To perform the microstructure characterization of scratched area, a series of scratches were produced on GaAs surface under various sliding velocities. To protect the surface from being destroyed by the focused ion beam (FIB), the polymer and Pt layer were coated in turn onto the sample. High-resolution cross section of scratches was detected by a transmission electron microscope (TEM, FEG Philips Tecnai F20, FEI, The Netherlands). Fig. 1 shows the process for TEM detection.

3. Experimental results and discussions

3.1. Material removal of GaAs surface at different sliding velocities

During many indentation and scratch tests, different types of indent holes and groove scratches were created on GaAs surface by mechanical interactions at a relatively high applied normal load or contact pressure [14,16]. However, plenty of defects may generate in the GaAs substrate during the indentation or scratching process, which can to some extent degrade the optical and electrical properties of GaAs-based quantum devices [21]. To avoid the damage in the subsurface of GaAs, the low-destruction material removal was attempted in the present study.

As shown in Fig. 2, the GaAs surface was scratched by a SiO_2 tip with R = 1.25 μm and under the applied normal load F_n = 2 μN. Under this condition, the maximum Hertzian contact pressure is estimated as less than 0.8 GPa, which is much lower than the critical contact pressure for the initial yield of GaAs surface (~4.9 GPa) [22]. However, the surface material along the scratching trace was removed and a groove was observed on GaAs surface by in situ AFM scanning.

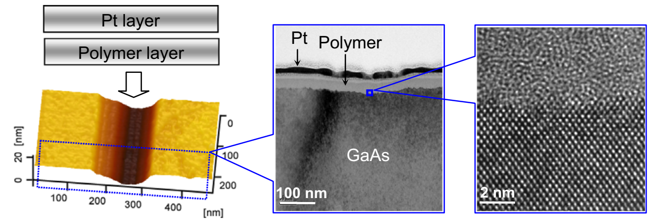

Fig. 1. The preparation and TEM detection processes of the groove on GaAs surface. To protect the surface of GaAs sample, the polymer layer and Pt film were coated in turn onto the scratched area. Following that, the groove was cut by FIB to obtain the cross section for TEM observation.

Since the plastic deformation will hardly take place during the scratching, it is hereby expected that the tribochemistry can play a key role in the material removal of GaAs surface, which is similar to that on silicon surface [10,20].

The variation of the groove depth is plotted in Fig. 3 as a function of the sliding velocity. It is noted that the sliding velocity reveals a strong effect on the formation of groove. With the increase in the sliding velocity from 0.1 μm/s to 1000 μm/s, the depth of the groove decreases sharply from 13.6 nm to 2.3 nm. During the scratching, the friction forces at different sliding velocities were measured and shown in Fig. 4. It is noted that the friction forces change little with the sliding velocity. Comparing to the large variation in the groove depth shown in Fig. 3, the fluctuation in friction force seems to have less impact on the material removal.

3.2. HRTEM detection

Generally, when the mechanical interaction dominates the wear process, the scratching on GaAs can lead to the severe deformation both on the contact surface and the subsurface [14,15]. In the present study, grooves were produced on GaAs surface under a very low load, as shown in Fig. 2. It was speculated that the tribochemical removal dominated the wear process and no destruction would be observed on the cross section of the scratched area of GaAs surface. To verify this, the cross-section microstructures of the grooves generated at various sliding speeds were observed by TEM, as shown in Fig. 5. No deformation, such as dislocation and crystal slipping, was found in the bulk matrix of GaAs from the TEM detection. The perfect GaAs matrix has been observed after the scratching at different speeds ranged between 0.1 μm/s and 1000 μm/s. It was noted that although the depth of material removal is greatly influenced by the sliding velocity, the sliding velocity has no effect on the microstructure of the cross-section of the grooves created under the low load. All these results confirmed that the mechanical wear via plastic deformation can be extremely restricted, and the tribochemical reaction has governed the material removal of GaAs surface during the scratching process at various sliding speeds.

3.3. Tribochemical mechanism for material removal on GaAs

It is reported that the adsorbed water and the materials of the counter tip play key roles in the tribochemical wear of surface during scratching [20,23]. In ambient air, GaAs surface can be hydroxylated by the adsorbed water, forming many dangling hydroxyl groups on the surface [24]. It was reported that GaAs–OH and Si–OH groups may polymerize during annealing and produce GaAs–O–Si bonding bridges [25]. During the scratching tests, the mechanical shear may input the energy into the contact pair. When the energy is high enough to pass the energy barrier, the tribochemical reaction may occur and the GaAs–O–Si bonding bridges will form between the counter-pair [25]. Since the bond energy of Si–O in SiO_2 (454 kJ/mol), Ga–O in GaOx (307–395 kJ/mol) and As–O in AsOx (~495 kJ/mol) are much higher than the bond energy of Ga–As (203 kJ/mol) [26],

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