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ARTICLE

# Ultra-precision Surface Polishing of Gallium Arsenide Wafer Using Magnetic Compound Fluid Slurry

**Wang Youliang**[1], **Liang Bo**[1], **Zhang Wenjuan**[2]

*[1] School of Mechanical and Electrical Engineering, Lanzhou University of Technology, Lanzhou 730050, China; [2] State Key Laboratory of Advanced Processing and Recycling of Nonferrous Metals, Lanzhou University of Technology, Lanzhou 730050, China*

**Abstract:** The effect of magnetic compound fluid (MCF) slurry on the gallium arsenide (GaAs) wafer surface after nano-precision polishing was investigated. MCF slurry was prepared by mixing CS carbonyl iron particles (CIPs), $Al_2O_3$ abrasive particles, $\alpha$-cellulose, and magnetic fluid. Firstly, a polishing device was assembled by designing MCF unit for the generation of revolving magnetic field. Then, the spot polishing experiments were performed on GaAs wafer surface to clarify the effects of MCF components on the surface roughness $R_a$ and material removal (MR) at different polishing positions. Finally, the scanning polishing experiments were conducted using water-based MCF slurry containing particles with different diameters. Results show that after spot polishing with water-based and oil-based MCFs, the initial surface roughness $R_a$ of 954.07 nm decreases to 1.02 and 20.06 nm, respectively. Additionally, the depth of MR is increased linearly with prolonging the polishing time. It is worth noting that the MR depth of surface after polishing with water-based MCF is 2.5 times higher than that with oil-based MCF. Meanwhile, the cross-section profile of the polished zone shows the W shape, which indicates the non-uniform MR on the workpiece surface after spot polishing. After scanning polishing, the cross-section profile of the polished zone shows the U shape, which indicates that MR is uniform under specific experiment conditions, regardless of the MCF types. The smoothest work surface with $R_a$=0.82 nm is achieved using MCF with abrasive particles of 0.3 μm in diameter, and MR rate is 13.5 μm/h.

**Key words:** magnetic compound fluid; GaAs wafer; polishing; surface roughness; material removal

Gallium arsenide (GaAs) wafer is one of the most important compound semiconductor materials due to its high electron mobility and low power consumption[1]. GaAs devices are mainly used in the field of microelectronics and solar energy[2]. In addition, GaAs wafer has great potential in both civil and military applications. To ensure the performance of GaAs wafer, the thickness and surface roughness need to satisfy the stringent requirements. When GaAs wafer is prepared by a single crystal, a surface damaged layer will be introduced onto the machined surface, which directly affects the stability of GaAs wafer[3–4]. To remove the damaged layer on the wafer surface, precise treatment of GaAs wafer is crucial. It is clear that the final process, namely polishing, is essential for requirement satisfaction. However, the excellent performance of GaAs wafer depends on not only the ultra-precision surface roughness, but also on the accurate thickness. Therefore, lapping is commonly used to achieve rapid material removal (MR). However, the damaged layer on the wafer surface cannot be completely removed after lapping. Thus, chemical etching is applied afterwards to remove the unqualified layer. Finally, the chemical mechanical polishing is used to remove the sub-surface damaged layer and to obtain the required ultra-smooth surface. MR rate (MRR) is normally investigated through the chemical mechanical polishing of GaAs using solutions of $H_2O_2$ and silica slurries containing $H_2O_2$[5]. The polishing parameters, such as polishing pressure, rotational speed, and fluid volume, are optimized to improve the polishing efficiency and surface quality by quantitative analysis method. The mechanisms of deformation and MR of GaAs wafers have been researched by molecular dynamics[6]. It is found that MR on GaAs surface is caused by the dynamical formation and break of interfacial chemical

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Corresponding author: Zhang Wenjuan, Ph. D., Assistant Professor, State Key Laboratory of Advanced Processing and Recycling of Nonferrous Metals, Lanzhou University of Technology, Lanzhou 730050, P. R. China, E-mail: 17794200112@163.com

bonds[7]. Those researches mainly focus on the optimization of polishing process, whereas the problems such as complex steps and long polishing time in traditional process are still unsolved. Hence, a novel method to achieve ultra-precision surface roughness is in urgent need.

Novel methods for ultra-precision surface polishing have been developed and ameliorated continuously, such as the magnetic field-assisted polishing, which uses magnetic fluid (MF) or magnetorheological fluid (MRF) as the base component of slurry. For example, the surface quality of a flat polypropylene workpiece can be significantly improved by MF polishing method[8]. A novel MR finishing tool is proposed to smoothen the flat surface of magnetic steel. After finishing process for 120 min, the final surface roughness of $R_a$ =19.7 nm can be obtained[9]. SKD11 material was polished by MRF and the optimal surface roughness is 1 μm[10]. The ferromagnetic surface can be finished by new magnetic abrasive method[11]. These researches all demonstrate that magnetic field-assisted polishing using MRF or MF shows great potential. However, under a given magnetic field, the particle distribution is less stable in MRF slurry than that in MF slurry, the magnetic pressure and apparent viscosity of MRF slurry are higher than those of the MF slurry, whereas the clusters are larger in MF than those in MRF slurry, leading to unstable performance in surface finishing process.

In order to overcome these problems and to maintain the excellent performance of MF and MRF slurries, a novel magnetic compound fluid (MCF) slurry is proposed[12]. It is prepared by mixing micrometer-sized carbonyl iron powders (CIPs), abrasive particles, and $\alpha$-cellulose into MF slurry containing nanometer-sized magnetite particles. The slurry is transformed rapidly and reversibly from Newtonian fluid to Bingham fluid under the external magnetic fields[13–14]. In addition, the behavior of magnetic particles within the as-prepared slurry can be regulated by the applied magnetic field, and MCF slurry shows excellent viscosity with better distribution of particles at the fluid state. The magnetic particles under the external magnetic fields are magnetized, thus forming a multitude of chain structures along the magnetic lines of force. Besides, the chain structures and the abrasive particles together form some stronger magnetic brushes[15]. Once a relative motion is applied between MCF slurry and wafer surface, a micro-cutting force is imposed onto the wafer surface owing to the induced friction between the abrasive particles and wafer surface[16]. Afterwards, the redundant material on the workpiece surface is removed slowly to obtain the ultra-smooth surface by micro-cutting action of the abrasive particles in MCF slurry. This novel slurry has been widely employed to finish various materials, such as oxygen-free copper, polymethyl methacrylate methacrylic acid, and Ni-P-plated STAVAX steel in engineering applications[17–19]. However, the GaAs wafer as the hard and brittle material is barely polished by the this novel MCF slurry.

In this research, an effective polishing technique for the nano-precision surface finishing of GaAs wafer was investigated. The finishing feasibility of GaAs wafer by MCF slurry was verified. The effects of MCF slurry composition and scanning path on the material removal were discussed. The surface roughness of the workpiece at different positions in the polishing area was analyzed.

## 1 Polishing Principle

Fig. 1 shows the schematic diagram of MCF polishing principle. A rotary magnetic field is generated by rotating the permanent magnet at specific speed ($n_m$), which is attached to the lower surface of magnet holder with an eccentricity of $r$. A certain amount of slurry is sprayed on the lower surface of MCF slurry carrier at the speed of $n_c$, which has the opposite direction to that of $n_m$. As shown in the right side of Fig.1, the chain-shaped magnetic clusters composed of micron-sized CIPs and nanometer-sized magnetite particles are formed along the magnetic lines of force immediately. Meanwhile, the abrasive particles are entrapped into the clusters or distributed between clusters, and then the $\alpha$-cellulose fibers interweave with the clusters. A large number of abrasive particles move towards the workpiece under the combined action of the magnetic levitation force and the gravity. In addition, the cluster structure is strengthened by the $\alpha$-cellulose fibers. The micro-cutting action of abrasive particles occurs to remove materials when the kinetic abrasive particles move on the wafer surface owing to the induced friction, leading to the smooth surface.

## 2 Experiment

According to the MCF polishing principle, an experiment device was designed and assembled, as shown in Fig. 2. The MCF carrier in polishing unit was prepared by aluminum plank and it was driven by a belt through motor 2. A cylindrical magnet ($\Phi$18 mm×10 mm, 0.4 T) with eccentricity $r$=4.5 mm was attached to the lower surface of magnet holder, which was controlled by motor 1. A dynamic revolving magnetic field was generated when the permanent magnet rotated with the magnet holder. Furthermore, the working gap between the workpiece and MCF carrier could be determined by adjusting $Z$-axis.

Table 1 shows the experiment parameters of MCF polishing

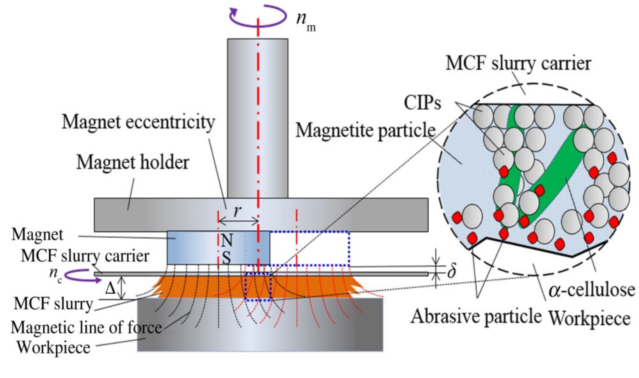


Fig.1 Schematic diagram of MCF polishing process

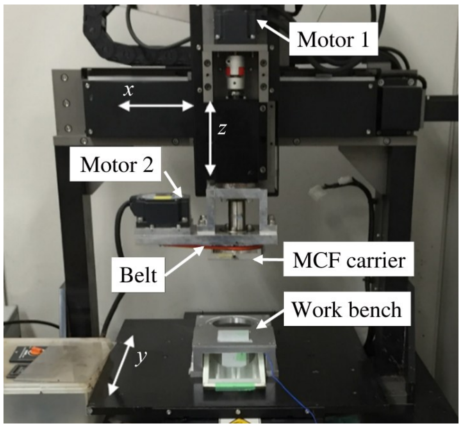


Fig.2 Appearance of experiment device

**Table 1 Experiment parameters of MCF polishing process with GaAs wafer as workpiece**

| Parameter | Value |
|---|---|
| Dimension of Nd-Fe-B magnet | $\Phi$18 mm×10 mm |
| Magnet eccentricity, $r$/mm | 4.5 |
| MCF carrier rotational speed, $n_c$/r·min$^{-1}$ | 800 |
| Magnet revolution speed, $n_m$/r·min$^{-1}$ | 1000 |
| MCF slurry volume, $V$/mL | 0.5 |
| Working gap, Δ/mm | 0.5 |
| Polishing time, $t$/min | 60, 120 |

process. A small working gap Δ=0.5 mm was employed, considering that the gallium arsenide wafer is a hard and brittle material. Because of the small machining gap, the filling volume of MCF slurry was 0.5 mL, and the new MCF was replaced after continuous polishing for 5 min to ensure that the MCF was at good polishing state. In this research, oil-based[20] and water-based MCF slurries were prepared, as shown in Table 2, to investigate the effects of MCF slurry composition on the surface roughness $R_a$ and MR. Four types of MCF slurries were prepared, and they were named as MCF1, MCF2, MCF3, and MCF4. After polishing, the wafer surface was washed by distilled water firstly, and then the surface was ultrasonically cleaned. Finally, the wafer surface was dried by compressed air rapidly. The cross section of the polished zone was observed by the surface profile (Talysurf

**Table 2 Composition of oil-based and water-based MCF slurries (wt%)**

| Material | Approximate size/μm | MCF1 | MCF2 | MCF3 | MCF4 |
|---|---|---|---|---|---|
| Oil-based MF | - | 40 | - | - | - |
| Water-based MF | - | - | 40 | 40 | 40 |
| CS CIPs | 7 | 45 | 45 | 45 | - |
| HQ CIPs | 1 | - | - | - | 45 |
| $\alpha$-cellulose | - | 3 | 3 | 3 | 3 |
| $Al_2O_3$ abrasive | 1 | 12 | 12 | - | 12 |
| particles | 0.3 | - | - | 12 | - |

Intra by Taylor Hobson) to determine MR state. The surface roughness was measured by the white-light interferometer (Zygo Newview 600 frp, Zygo Corp).

## 3 Results and Discussion

### 3.1 Spot polishing

The schematic diagram of GaAs wafer after polishing by MCF slurry for 60 min is shown in Fig. 3. To explore the distribution of surface roughness in the polishing area, the surface roughness at five small areas (A, B, O, B′, A′) along the central line was measured. Therefore, the average value was defined as the polished surface roughness for the further analysis.

Fig. 4 shows the changes of surface roughness $R_a$ of GaAs wafer after polishing by different MCF slurries for different durations. It can be observed that the surface roughness is decreased with increasing the polishing time, regardless of the MCF slurry type. It is worth noting that the surface roughness decreases quickly at the initial 30 min and then it decreases slowly. The surface roughness tends to be stable after MCF polishing for 60 min. However, it still fluctuates, indicating that the polished surface is uneven. Besides, the fluctuation amplitude with MCF2 slurry is larger than that with MCF1 slurry. The surface roughness at five different areas after polishing with MCF2 slurry is shown in Fig. 5. It can be seen that at the center of the polishing area (area O), the surface roughness decreases to 200 nm after polishing for 120 min,

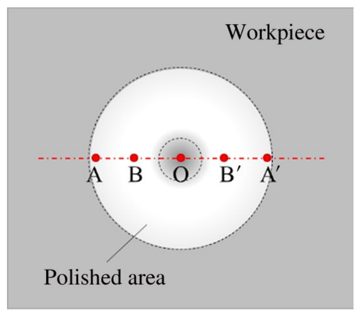


Fig.3 Schematic diagram of workpiece after MCF polishing for 60 min

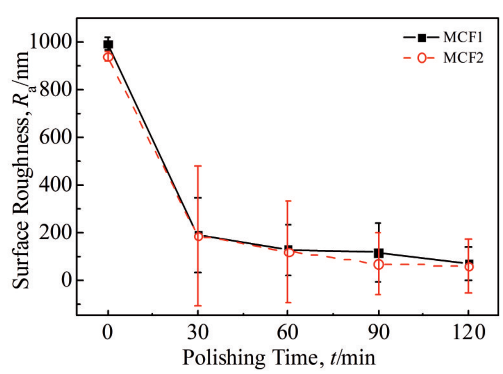


Fig.4 Surface roughness $R_a$ of GaAs wafer after polishing by different MCF slurries for different durations

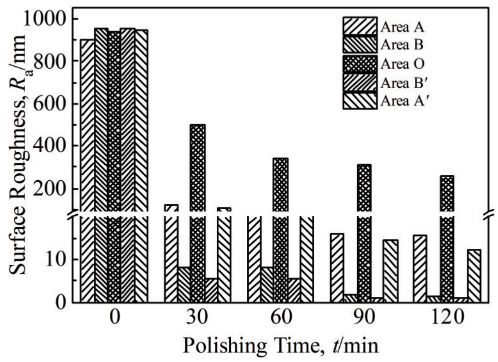


Fig.5 Surface roughness $R_a$ at different areas on GaAs wafer after spot polishing by MCF2 slurry for different durations

which is much larger than that of other areas. The surface roughness of area B and area B′ is quite small of 1.36 and 1.02 nm, respectively. The surface roughness of area A and area A′ (the edge of polishing area) is 15.5 and 12.2 nm, respectively, which is about 10 times larger than that of area B. The surface roughness of area O is 255.18 nm, which is 187 times higher than that of area B.

The 3D images of wafer surface before and after polishing are shown in Fig.6. The initial wafer surface is rough with $R_a$= 954.07 nm. After polishing for 120 min, smooth surfaces with $R_a$=20.06 nm and $R_a$=1.02 nm can be obtained by polishing with oil-based and water-based MCF slurries, respectively. The results indicate that the water-based MCF slurry is more suitable for GaAs wafer polishing. As shown in Fig. 6b, the small convex particles can be observed on the wafer surface after polishing by oil-based MCF slurry, resulting in the worse surface roughness. The removal trace of abrasive particles is obvious. The oil in MCF slurry decreases the friction coefficient between the abrasive particles and wafer surface, resulting in the smaller micro-cutting force on the GaAs wafer. The convex particles can hardly be removed in a short time. The GaAs wafer surface is smoother after polishing with water-based MCF slurry, as shown in Fig. 6c. The minimum surface roughness is 1.02 nm, which is much smaller than that polished by MCF1 slurry.

The surface roughness is closely related to MR state of workpiece surface. So the cross-sectional profile of polishing area was observed to discuss the effect of MCF slurry on MR. The cross-section profile and 3D structure of typical polished area after polishing with MCF2 slurry for 30 min are shown in Fig.7. It can be seen that the wafer surface before polishing is flat, and the cross-section profile after polishing shows W shape, suggesting that MR has the characteristic of symmetrical distribution. MR begins at the edge of polishing area and then deepens to reach the maximum value of 4.6 mm. Afterwards, MR becomes shallow again. Compared with Fig. 5, it can be found that the more the material removes, the smoother the surface, i.e., MR occurs more severely in area B and area B′ and the surface roughness of those areas is obviously lower. The maximum depth is used to reflect MR in this research. The material of workpiece surface is removed unevenly, resulting in the fluctuation of surface roughness (Fig. 4) and various surface roughness at different areas (Fig.5).

The MR depth variation of wafer surface after polishing by MCF1 and MCF2 slurries is shown in Fig. 8. It can be observed that MR depth is approximately linearly increased with prolonging the polishing time. Additionally, MR depth under MCF2 slurry condition is larger than that under MCF1 slurry condition. After polishing for 120 min, MR depth is about 10 μm using MCF1 slurry containing oil-based MF, whereas it is 25 μm using MCF2 slurry, which is 2.5 times larger than that using MCF1 slurry. For the GaAs wafer finishing, more MR and smoother surface can be obtained using the water-based MCF slurry. However, after spot polishing, MR in the polishing area is not uniform, which seriously affects the flatness of the polished GaAs wafer. In order to obtain more uniform MR, the scanning polishing was further conducted.

### 3.2 MR under scanning polishing

MR is related to the friction coefficient, polishing pressure, and relative velocity between abrasive particles in MCF slurry and workpiece surface under the external magnetic field. The friction coefficient between the abrasive particles and workpiece surface is constant, whereas the polishing pressure of MCF slurry acting on the polishing area varies according to the magnetic field intensity, which results in different polishing pressures of particles. The relative velocity depends on the rotational speed of magnet. In order to obtain the uniform MR, the forces acting on single CIP and abrasive particle under the magnetic field are analyzed, as shown in Fig. 9. When MCF slurry containing abrasive particles is under an external magnetic field, a magnetic levitation force $F_{AP}$ is applied on abrasive particle. Besides, a magnetic field force $F_{CIP}$ is applied on CIP which is located on the top of abrasive particle. Because CIP is at the equilibrium state, an opposite force is applied on the single

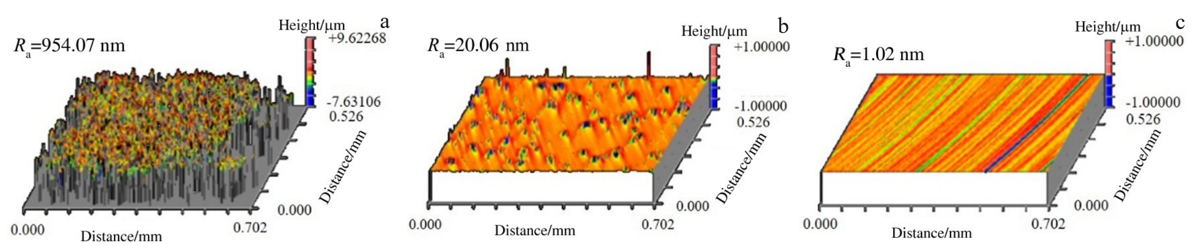


Fig.6 3D images of work surface before (a) and after spot polishing by MCF1 slurry (b) and MCF2 slurry (c)

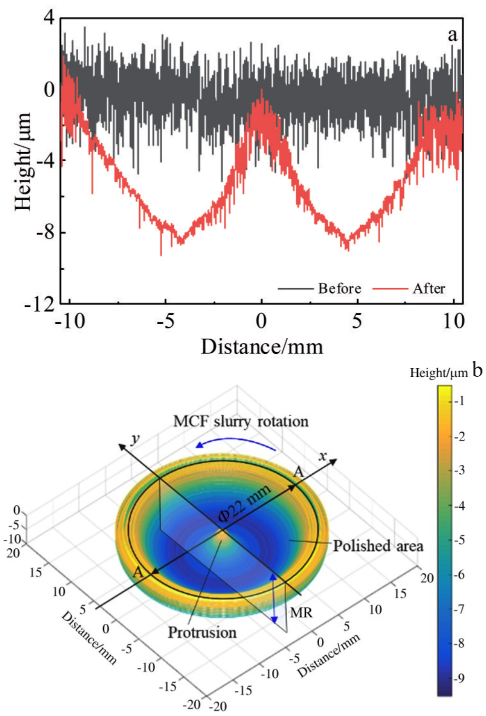


Fig.7 Cross-sectional profile (a) and 3D structure (b) of typical polished area after spot polishing by MCF2 slurry

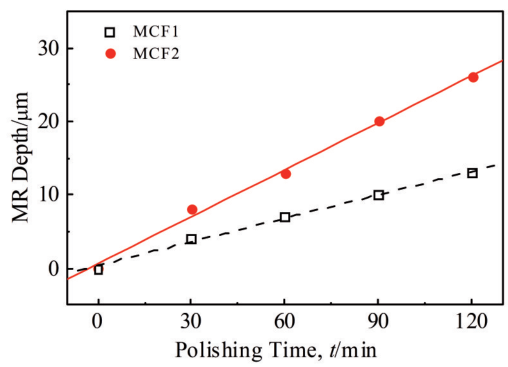


Fig.8 MR depth of wafer surface after spot polishing by MCF1 and MCF2 slurries for different durations

abrasive particle. Therefore, the indentation on the workpiece surface is generated by abrasive particle with magnetic field force $F_{AP\text{-}z}$ and an opposite magnetic field force in $z$ direction $-F_{CIP\text{-}z}$. The embedding depth of abrasive particle acting on the workpiece surface reflects MR in MCF polishing process. Thus, MR can be obtained by Eq. (1), as follows:

$$H_B = \frac{2F_z}{\pi D_{AP}\left(D_{AP} - \sqrt{D_{AP}^2 - D_i^2}\right)} \tag{1}$$

where $H_B$ is the Brinell hardness of the GaAs workpiece (7350 N/mm$^2$), $F_z$ is the resultant force acting on an abrasive particle under the magnetic field, $D_{AP}$ is the diameter of an abrasive particle (1 μm), and $D_i$ is the diameter of formed indentation by the action of abrasive particle on the workpiece surface. According to Eq. (1), $D_i$ can be expressed by Eq. (2), as follows:

$$D_i = \sqrt{\frac{4F_z}{\pi H_B} - \frac{4F_z^2}{\left(\pi D_{AP} H_B\right)^2}} \tag{2}$$

According to Fig.9, $F_z$ can be defined as follows:

$$F_z = -F_{CIP\text{-}z} + F_{AP\text{-}z} \tag{3}$$

Then, the embedding depth of the abrasive particle acting on the workpiece surface can be expressed as follows:

$$d_i = \frac{1}{2}\left(D_{AP} - \sqrt{D_{AP}^2 - D_i^2}\right) \tag{4}$$

where $d_i$ is the embedding depth of single abrasive particle acting on the workpiece surface.

In the process of MCF polishing, CIPs in MCF fluid is affected by the magnetic force, gravity, viscous resistance, Van der Waals force, and buoyancy. As shown in Fig.9, among these forces, magnetic force is the main factor affecting CIPs in the polishing process. Therefore, the force on CIP is as follows:

$$\boldsymbol{F}_{CIP} = \mu_0(\boldsymbol{m}\cdot\nabla)\boldsymbol{H} \tag{5}$$

where $\mu_0$ is the permeability of vacuum; $\boldsymbol{m}$ is the magnetic dipole moment of CIP; $\boldsymbol{H}$ is the magnetic field; $\nabla$ indicates the Hamiltonian operator. CIP can be regarded as the magnetic dipole owing to its extremely small size.

The value of $\boldsymbol{m}$ can be further determined by CIP volume ($V_{CIP}$), CIP magnetic susceptibility ($\chi_m$), CIP magnetic permeability ($\mu$), vacuum permeability ($\mu_0$), and magnetic field $\boldsymbol{H}$. The relationship equation is as follows:

$$\boldsymbol{m} = V_{CIP}\chi_m \frac{3\mu_0}{\left(\mu + 2\mu_0\right)}\boldsymbol{H} \tag{6}$$

Then, the coordinate system ($x$, $y$, $z$) is defined, as shown in Fig.2. The Hamiltonian operator $\nabla$ is as follows:

$$\nabla = \frac{\partial}{\partial x}\boldsymbol{i} + \frac{\partial}{\partial y}\boldsymbol{j} + \frac{\partial}{\partial z}\boldsymbol{k} \tag{7}$$

where $\boldsymbol{i}$, $\boldsymbol{j}$, and $\boldsymbol{k}$ are the unit vectors in the coordinate system. Thus, the magnetic field vector can be obtained by Eq.(8), as follows:

$$\boldsymbol{H} = H_x\boldsymbol{i} + H_y\boldsymbol{j} + H_z\boldsymbol{k} \tag{8}$$

where $H_x$, $H_y$, and $H_z$ are the components of the magnetic field in the $x$, $y$, and $z$ directions, respectively.

Then, the forces on CIP is expressed as follows:

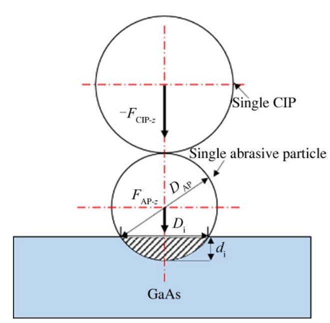


Fig.9 Schematic diagram of forces acting on CIP and abrasive particle under external magnetic field

$$\boldsymbol{F}_{\mathrm{CIP}} = F_{\mathrm{CIP}\text{-}x}\boldsymbol{i} + F_{\mathrm{CIP}\text{-}y}\boldsymbol{j} + F_{\mathrm{CIP}\text{-}z}\boldsymbol{k} \tag{9}$$

with

$$F_{\mathrm{CIP}\text{-}x} = \frac{3V_{\mathrm{CIP}}\chi_{\mathrm{m}}\mu_0^2}{\mu + 2\mu_0}\left(H_x\frac{\partial H_x}{\partial x} + H_y\frac{\partial H_x}{\partial y} + H_z\frac{\partial H_x}{\partial z}\right) \tag{10}$$

$$F_{\mathrm{CIP}\text{-}y} = \frac{3V_{\mathrm{CIP}}\chi_{\mathrm{m}}\mu_0^2}{\mu + 2\mu_0}\left(H_x\frac{\partial H_y}{\partial x} + H_y\frac{\partial H_y}{\partial y} + H_z\frac{\partial H_y}{\partial z}\right) \tag{11}$$

$$F_{\mathrm{CIP}\text{-}z} = \frac{3V_{\mathrm{CIP}}\chi_{\mathrm{m}}\mu_0^2}{\mu + 2\mu_0}\left(H_x\frac{\partial H_z}{\partial x} + H_y\frac{\partial H_z}{\partial y} + H_z\frac{\partial H_z}{\partial z}\right) \tag{12}$$

where $F_{\text{CIP-}x}$, $F_{\text{CIP-}y}$, and $F_{\text{CIP-}z}$ are the components of magnetic force in $x$, $y$, and $z$ directions, respectively; $\partial H_x/\partial x$, $\partial H_x/\partial y$, and $\partial H_x/\partial z$ are the gradient of $H_x$ in $x$, $y$, and $z$ directions, respectively; $\partial H_y/\partial x$, $\partial H_y/\partial y$, and $\partial H_y/\partial z$ are the gradient of $H_y$ in $x$, $y$, and $z$ directions, respectively; $\partial H_z/\partial x$, $\partial H_z/\partial y$, and $\partial H_z/\partial z$ are the gradient of $H_z$ in $x$, $y$, and $z$ directions, respectively.

In fact, the single abrasive particle is also affected by many other forces during the polishing process. Among them, the magnetic levitation force is the primary factor affecting the working particles, and the force on single abrasive particles is as follows:

$$\boldsymbol{F}_{\mathrm{AP}} = -\mu_0 V_{\mathrm{AP}}(\boldsymbol{M}\cdot\nabla)\boldsymbol{H} \tag{13}$$

where $V_{\mathrm{AP}}$ is the volume of abrasive particle and $\boldsymbol{M}$ is the magnetization intensity of the magnetic fluid. $\boldsymbol{M}$ can be defined as follows:

$$\boldsymbol{M} = \chi'_{\mathrm{m}}\boldsymbol{H} \tag{14}$$

where $\chi'_{\mathrm{m}}$ is MCF magnetic susceptibility. Thus, the force on single abrasive particle is as follows:

$$F_{\mathrm{AP}} = F_{\mathrm{AP}\text{-}x}\boldsymbol{i} + F_{\mathrm{AP}\text{-}y}\boldsymbol{j} + F_{\mathrm{AP}\text{-}z}\boldsymbol{k} \tag{15}$$

with

$$F_{\mathrm{AP}\text{-}x} = -\mu_0 V_{\mathrm{AP}}\chi'_{\mathrm{m}}\left(H_x\frac{\partial H_x}{\partial x} + H_y\frac{\partial H_x}{\partial y} + H_z\frac{\partial H_x}{\partial z}\right) \tag{16}$$

$$F_{\mathrm{AP}\text{-}y} = -\mu_0 V_{\mathrm{AP}}\chi'_{\mathrm{m}}\left(H_x\frac{\partial H_y}{\partial x} + H_y\frac{\partial H_y}{\partial y} + H_z\frac{\partial H_y}{\partial z}\right) \tag{17}$$

$$F_{\mathrm{AP}\text{-}z} = -\mu_0 V_{\mathrm{AP}}\chi'_{\mathrm{m}}\left(H_x\frac{\partial H_z}{\partial x} + H_y\frac{\partial H_z}{\partial y} + H_z\frac{\partial H_z}{\partial z}\right) \tag{18}$$

where $F_{\text{AP-}x}$, $F_{\text{AP-}y}$, and $F_{\text{AP-}z}$ are the components of the magnetic force in $x$, $y$, and $z$ directions, respectively.

Substituting Eq.(12) and Eq.(18) into Eq.(3), the resultant force in $z$ direction on single abrasive particle can be obtained, as follows:

$$F_z = \left(\frac{3V_{\mathrm{CIP}}\chi_{\mathrm{m}}\mu_0^2}{\mu + 2\mu_0} + \mu_0 V_{\mathrm{AP}}\chi'_{\mathrm{m}}\right)\left(H_x\frac{\partial H_z}{\partial x} + H_y\frac{\partial H_z}{\partial y} + H_z\frac{\partial H_z}{\partial z}\right) \tag{19}$$

In addition, the number of abrasive particles per circle can be defined, as follows:

$$N = \frac{2\pi r_{\mathrm{x}}}{D_{\mathrm{AP}}} \times 10^3 \tag{20}$$

where $r_{\mathrm{x}}$ is the radius of the active abrasive particle during the polishing process.

MCF process can remove a very small amount of material by penetration and rotation of abrasive particles on the wafer surface. The MR depth by abrasive particles is equal to the product of indentation depth of abrasive particles and finishing length. Thus, the MR depth ($d_{\mathrm{MR}}$) is calculated, as follows:

$$d_{\mathrm{MR}} = \int_0^t d_{\mathrm{i}} N \frac{n_{\mathrm{c}}}{60}\mathrm{d}t \tag{21}$$

where $n_{\mathrm{c}}$ is the rotational speed of the permanent magnet.

MR depth can be obtained from Eq.(2), Eq.(4), and Eq.(19–21), as follows:

$$\begin{aligned} d_{\mathrm{MR}} = -\int_0^t \frac{n_{\mathrm{c}} r_{\mathrm{x}}\pi}{180H_B}\left(\frac{3V_{\mathrm{CIP}}\chi_{\mathrm{m}}\mu_0^2}{\mu + 2\mu_0} + \mu_0 V_{\mathrm{AP}}\chi'_{\mathrm{m}}\right) \\ \times\left(H_x\frac{\partial H_z}{\partial x} + H_y\frac{\partial H_z}{\partial y} + H_z\frac{\partial H_z}{\partial z}\right)\mathrm{d}t \quad r_{\mathrm{x}} \in (-11, 11) \end{aligned} \tag{22}$$

In this research, CIPs and abrasive particles are considered as spherical particles with diameter of 7 and 1 μm and density of $7.8\times10^{-3}$ and $3.965\times10^{-3}$ kg/m$^3$, respectively. The Brinell hardness of GaAs wafer is 7350 N/mm$^2$. The vacuum permeability $\mu_0$ is $4\pi\times10^{-7}$ N/A$^2$. CIP magnetic permeability $\mu$ is $5.03\times10^{-7}$ N/A$^2$. CIP magnetic susceptibility $\chi_{\mathrm{m}}$ is $1\times10^{-3}$. MCF magnetic susceptibility $\chi'_{\mathrm{m}}$ is 0.669. Substituting these parameter values into Eq.(22), the theoretical curve of MR can be obtained, and the results are shown in Fig.10.

It can be seen that the theoretical curve shows a W shape after MCF polishing, which is consistent with the results of polishing experiment. In addition, the values of the fitting curve are slightly smaller than the experimental values, because the influence of magnetic force on the single abrasive particle is considered in the calculation in order to simplify the model. In the simulation study, the flow behavior of MCF is considered as laminar flow for simplification. In the tests, the flow behavior of MCF is too complex to be directly simulated, resulting in errors. As a result, MR on the workpiece surface using MCF is related to not only the polishing force, but also to the velocity of relative movement between the abrasive particles in MCF slurry and the workpiece surface. Therefore, the uniform MR can be obtained by adjusting the polishing track, which changes the polishing force and velocity of relative movement.

### 3.3 Scanning polishing

The water-based MCF slurry was used to polish the GaAs wafer along the scanning path due to its better MR effect and smoother surface, compared with the oil-based MCF slurry. In order to obtain the uniform MR and fine surface roughness, the selection of appropriate step length is crucial. Therefore,

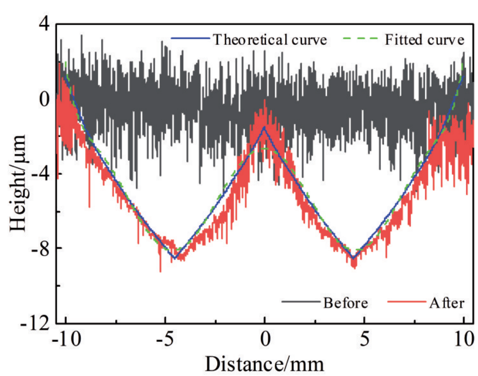


Fig.10 Experimental and simulated MR depth of GaAs wafer surface after polishing

the step length should be less than 4.6 mm, which is the maximum MR depth, according to the cross-section profile in Fig.10.

The polishing unit moves along the polishing path, as shown in Fig.11. It can be observed that the step length of the polishing unit is set as 4.6 mm in both $x$-axis and $y$-axis directions in order to achieve the optimal processing efficiency. The motion speed is 1 mm/s, the polishing time is 60 min, and other polishing parameters are the same as those experiment parameters in Table 1.

The experiment results of workpiece surface after scanning polishing for 60 min are shown in Fig. 12. It can be clearly seen that the cross-section profile of workpiece surface before MCF scanning polishing is basically straight, indicating that the workpiece surface is flat. The surface is kind of rough due to the irregular burrs caused by the previous process. After scanning polishing, the cross-section profile of workpiece surface presents a U shape, regardless of the MCF slurry types. Besides, the uncleared material in the center area after spot polishing is removed after scanning polishing. As shown in Fig. 12, MR of workpiece surface starts from the edge of polishing area, gradually deepens to the maximum value, and finally tends to stable at the other edge. It is worth noting that the maximum MR depth of the polishing area is about 13.5 μm using the MCF2 slurry containing CIPs with diameter of 7 μm and abrasive particles with main diameter of 1 μm. Meanwhile, the minimum MR depth is about 7.02 μm using the MCF4 slurry containing CIPs of 1 μm in diameter and abrasive particles of 1 μm in diameter, which is only 52% of that using MCF2 slurry. The MR depth is 9.69 μm, using the MCF4 slurry containing CIPs with diameter of 7 μm and abrasive particles with the main diameter of 0.3 μm. Therefore, the MR results indicate that the MCF slurry containing particles with the same diameter has adverse effect on MR. Additionally, the abrasive particles with larger size is beneficial to remove material.

Fig. 13 shows the surface roughness at different areas on GaAs wafer after scanning polishing by MCF3 slurry for different durations. After scanning polishing for 60 min, the surface quality in the polishing area greatly improves. However, the surface roughness of area A and area A′ at the edge of polishing area with less MR is obviously larger than that of area B, area O, and area B′ with more MR. The surface

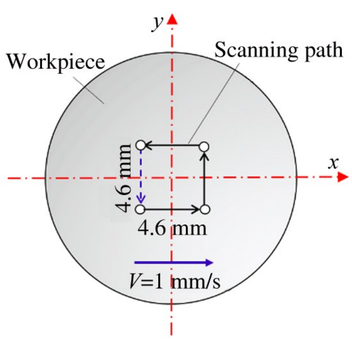


Fig.11 Schematic diagram of MCF polishing along scanning path

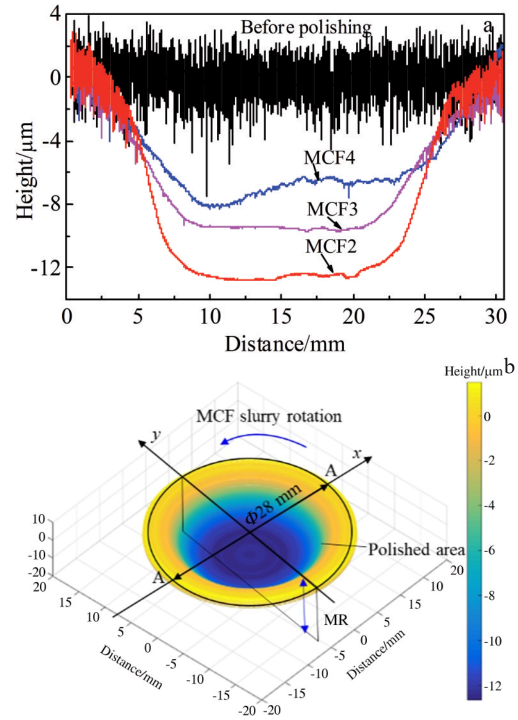


Fig.12 Cross-section profile (a) and 3D structure (b) of typical polished area after scanning polishing

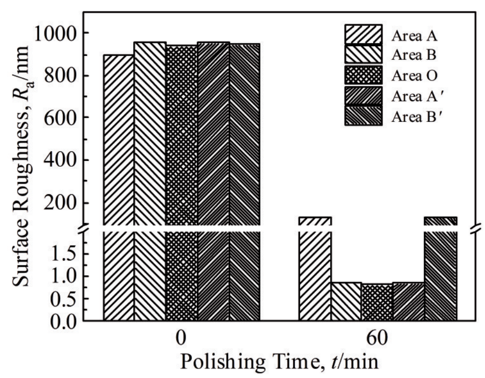


Fig.13 Surface roughness $R_a$ at different areas on GaAs wafer after scanning polishing by MCF3 slurry for different durations

roughness of area B, area O, and area B′ is basically the same. The optimal surface roughness is 0.82 nm at the center of polishing area, whereas that area is rough after spot polishing under the same experiment conditions. This phenomenon indicates that all surface in the polishing area can be smoothened by the scanning polishing. Fig. 14 exhibits the surface morphologies at the center of polishing area with different MCF slurries. Compared with the spot polishing results (Fig.6), the surface roughness of GaAs wafer improves by 85% after scanning polishing with MCF2 slurry.

After scanning polishing with different MCF slurries for 60 min, the surface roughness and MRR are shown in Fig. 15. MRR is 13.5, 9.69, and 7.02 μm/h using MCF2, MCF3, and MCF4 slurries, respectively. The surface roughness decreases

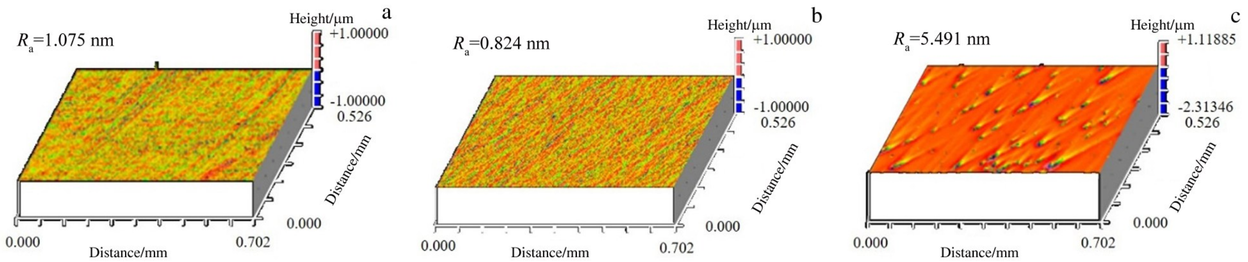

Fig.14 Surface morphologies at the center of polishing area after scanning polishing with MCF2 slurry (a), MCF3 slurry (b), and MCF4 slurry (c)

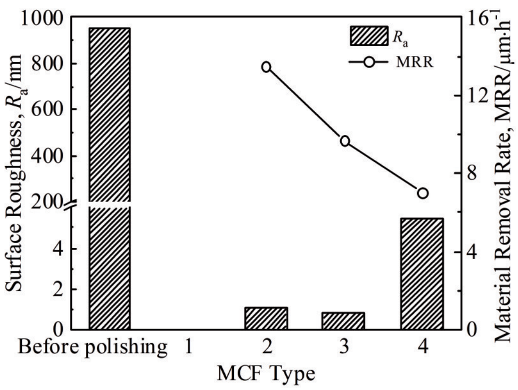

Fig.15 Surface roughness ($R_a$) and MR rate (MRR) after scanning polishing for 60 min with different MCF slurries

obviously to several nanometers after polishing for 60 min. The optimal surface roughness can be achieved using MCF3 slurry containing smaller abrasive particles, compared with that using MCF2 and MCF4 slurries. This result suggests that smaller abrasive particles are beneficial to smoothen the surface. The specimen with MCF2 slurry has the highest MRR, followed by MCF3 and MCF4 slurries, revealing that bigger CIPs and abrasive particles are beneficial to rapidly remove the material. Additionally, the same diameter of CIPs and abrasive particles in MCF4 slurry is harmful to simultaneously meet the requirements of high MR and low surface roughness. It is worth noting that the surface is obviously different using MCF4 slurry: the pits are shallow and the polishing trace can still be observed. These phenomena all indicate the inferior surface quality. Moreover, the defect cannot be removed completely after polishing with MCF4 slurry, and the surface roughness $R_a$ is 5.49 nm. This research shows that the application of MCF slurry in the ultra-precision polishing of hard and brittle materials is feasible.

## 4 Conclusions

1) GaAs wafer surface can be smoothened by the magnetic compound fluid (MCF) slurry. Larger material removal and smoother surface can be achieved through the water-based MCF slurry, compared with the oil-based MCF slurry. The cross-section profile of workpiece after spot polishing shows the W shape, indicating that the material removal is uneven. The material removal is increased linearly with prolonging the polishing time.

2) The wafer surface after scanning polishing with water-based MCF slurry shows the U shape. The optimal surface has the roughness of 0.82 nm after spot polishing with the MCF slurry containing smaller abrasive particles. Besides, the maximum surface roughness is 5.49 nm after polishing with the MCF slurry containing the carbonyl iron particles (CIPs) and abrasive particles of the same diameter.

3) Bigger CIPs and abrasive particles are beneficial to rapidly remove the material, whereas the same diameter of CIPs and abrasive particles in MCF slurry is harmful to simultaneously meet the requirements of high material removal and low surface roughness. Compared with the spot polishing results, the surface roughness of GaAs wafer improves by 85% after scanning polishing using specific slurry.

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# 磁性复合流体对砷化镓晶片的超精密表面抛光

王有良[1]，梁　博[1]，张文娟[2]
(1. 兰州理工大学 机电工程学院，甘肃 兰州 730050)
(2. 兰州理工大学 省部共建有色金属先进加工与再利用国家重点实验室，甘肃 兰州 730050)

**摘　要：**研究了磁性复合流体（MCF）浆料对砷化镓（GaAs）晶片表面纳米精密抛光的影响。通过混合CS羰基铁颗粒（CIPs）、$Al_2O_3$磨料颗粒、*α*-纤维素和磁性流体制备MCF浆料。首先，通过设计用于产生旋转磁场的MCF单元，建立了抛光装置。然后，对GaAs晶片表面进行了点抛光实验，以阐明MCF成分对不同抛光位置的表面粗糙度$R_a$和材料去除（MR）的影响。最后，使用含有不同直径颗粒的水基MCF浆料进行了扫描抛光实验。结果表明，在点抛光的情况下，水基和油基MCF处理后的初始表面粗糙度从954.07 nm分别降至1.02和20.06 nm。此外，MR的深度随着抛光时间的增加而线性增加。使用水基MCF的MR深度是使用油基MCF抛光的2.5倍。同时，抛光区的横截面轮廓显示出W型，这表明点抛光工件表面的MR不均匀。通过扫描抛光，抛光区的横截面轮廓显示出U型，这表明在给定的实验条件下，无论使用何种MCF，MR都是均匀的。使用含有直径为0.3 μm的磨粒的MCF能够获得$R_a$为0.82 nm的最光滑工件表面，同时MR速率为13.5 μm/h。

**关键词：**磁性复合流体；砷化镓晶片；抛光；表面粗糙度；材料去除

作者简介：王有良，男，1986年生，博士，副教授，兰州理工大学机电工程学院，甘肃 兰州 730050，E-mail：wangyouliang20@lut.edu.cn