Electronic Supplementary Material (ESI) for Nanoscale

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Laser patterning of conductive gold micronanostructures from nanodots

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Experimental

Characterization

The surface morphologies of the samples were measured on a JEOL JSM-6700F field emission scanning electron microscope (FE-SEM) operating at 3.0 keV. The gold nanodots were characterized through JEOL-2100F transmission electron microscope (TEM) at 200 kV. X-ray photoelectron spectroscopy (XPS) was performed using an ESCALAB 250 spectrometer. The distribution of the elements were collected by JSM 7001F Energy Dispersive X-ray Detector (EDX).

Caculation of gradient optical force

Optical force is gradient to the light intensity according to the formula:

$$F=\frac{\alpha}{2}\nabla(E^2),\ \propto \nabla I$$

The light force is uniform in the direction of light propagating only in freespace. However, in our work, light is tightly focused by objective lens. Intensity is a Gaussian distribution perpendicular to the light propagating. Waist radius changes dramatically from 1mm to about 286nm while the propagating distance is 200 μm. Light intensity distribution of 10mw is showed in Fig. 7a. Light force is estimated by Formula 1 as Fig. 7b and maximum force near the focal point is about 7.28 pN.

The calculated results of the Gassian field strength and the optical gradient force distribution through MATLAB (Matrix Laboratory) program according classic Gassian equation and made some calculus to get the gradient force (shown in the supporting imformation).

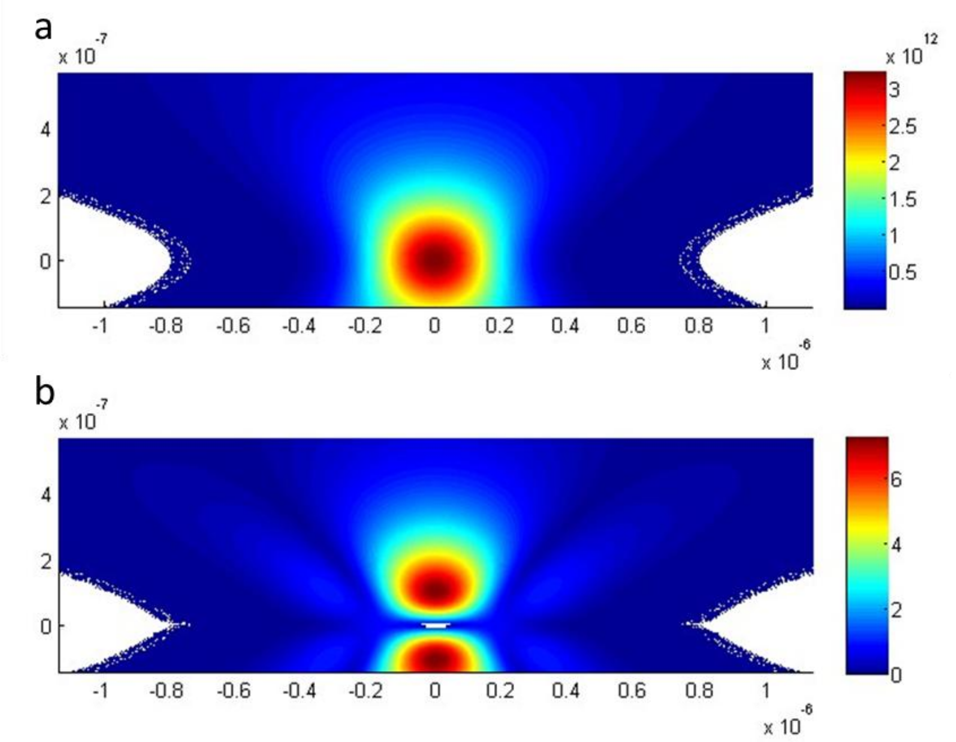

Fig. SI-1 The simulating results of the laser field strength and the gradient force distribution.

Laser wavelength: 800 nm; Object lens: 100×, NA=1.4

Laser power: $P=10\times10^{-3}$w,

Single pulse power: $P_s=\frac{F}{R_{Hz}*t_0}=1.04\times10^3$w. The laser repetition rate: R_{Hz}. Pulse width: t_0.

Waist radius at position z: $w(z)=w_0\sqrt{1+\frac{\lambda^2 z^2}{\pi w_0^4}}$;

w_0: Waist radius at focused position which is equavilent to the focused spot radius, D/2.

$D\approx\frac{\lambda}{NA}$, $w_0=286$nm

At position z, the electric field strength amplitude at the center of cross-section:

$$E=\frac{E_0}{w(z)}*\exp(-\frac{x^2+y^2}{w(z)^2})*\exp[-ik(\frac{x^2+y^2}{2r(z)}+z)+i\varphi(z)]$$

At position z,the Gaussian field strength amplitude of cross-section:

$$I(x,y)=|E^2|=(\frac{E_0}{w(z)})^2*\exp(-2\frac{x^2+y^2}{w^2(z)})=(\frac{E_0}{w(z)})^2*\exp(-2\frac{r^2}{w^2(z)}),\ \text{where } r^2=x^2+y^2;$$

At the position of testing power, w(z)=w1,

$$P=\iint_S I(x,y)dxdy=\int_0^{2\pi}\int_0^{\infty}(\frac{E_0}{w_1})^2*\exp(-2\frac{r^2}{w_1^{\ 2}})drd\theta=2\pi E_0^{\ 2}*\frac{1}{\sqrt{2}w_1}*\frac{\sqrt{\pi}}{2}=\pi^{3/2}E_0^2\frac{1}{\sqrt{2}w_1}$$

$$E_0^2=\frac{\sqrt{2}w_1}{\pi^{3/2}}P=0.265;$$

$$|E^2|=(\frac{E_0}{w(z)})^2*\exp(-2\frac{x^2+y^2}{w(z)^2})=\frac{\sqrt{2}w_1}{\pi^{3/2}w^2(z)}P*\exp(-2\frac{x^2+y^2}{w(z)^2})$$

The maximum value of $|E^2|$ is $3.24\times10^{12}(v/m)^2$

The size of gold nanodots, a=4 nm

$\varepsilon_1=-26.159;\varepsilon_2=1.853$

$\varepsilon=\varepsilon_1+\varepsilon_2*i=-26.159+i*1.853$

$n_s=1.32908$

$\varepsilon_s=n_s^{\ 2}=1.77$

$k=\sqrt{-\varepsilon_1/2+\sqrt{(\varepsilon_1.^2+\varepsilon_2^{\ 2})/2}}=5.12$

Skin depth: $\delta=\frac{\lambda}{2\pi k}=24.88$nm, $V=4\pi\iint\frac{r^2 exp(r-a)}{\delta}drd\theta$

$\alpha=3V\frac{\varepsilon-\varepsilon_s}{\varepsilon+2\varepsilon_s}=4.37*10^{-22}+6.76*10^{-24}i$

$|\alpha|=4.38*10^{-22}$

$F=\frac{|\alpha|}{2}grad(|E^2|)$

At position The maximum value of F is 7.28 pN at the Z axis

The thermal characteristics of the gold nanodots

The thermal characteristics of the gold nanodots were examined by a thermogravimetric analysis (TGA) and a differential scanning calorimeter (DSC) with 10 °C min^{-1} scanning rate. Dramatic changes in the weight and heat flow signify the melting of the gold nanodots around 190 °C. When applied enough laser power, the corresponding heat generated would make the nanodots fused on the pattern surface.(Fig. 5)

In conclusion, the optical gradient force play a major role in driving and pattering the metal nanodots to the substrate and the light-heat effect influence the surface morphologies including roughness and specific ripples of gold microstructures.

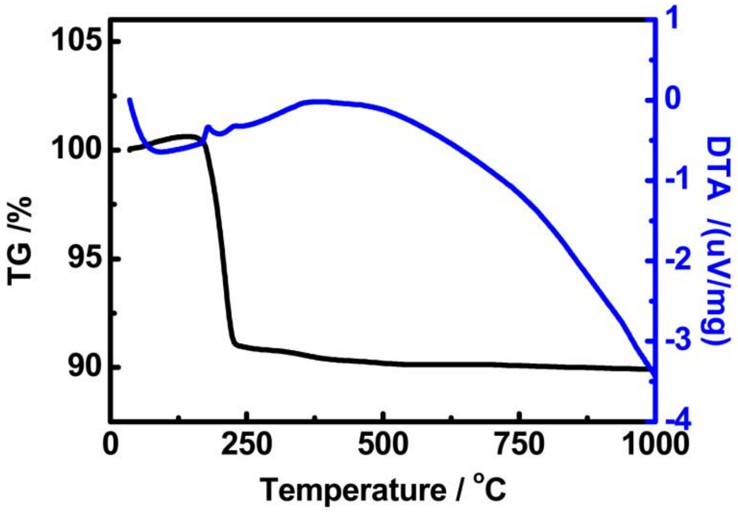

Fig. SI-2 TGA and DSC measurements showed that the gold nanodots melted around 190 °C.

The resistivity characterization of laser created gold wire

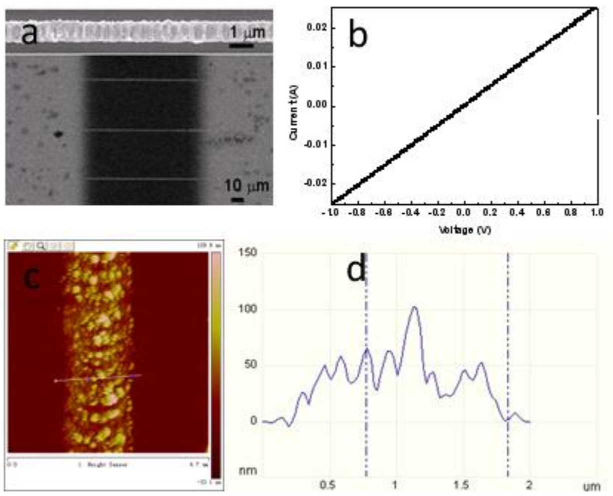

Fig. SI-3 Resistivity characterization of patterned gold microlines

The stable electrical property of gold microstructures

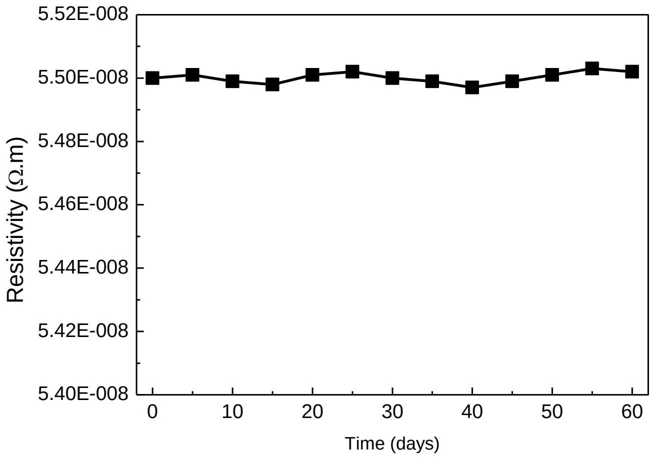

Fig. SI-4 The resistivity almost doesn’t change with time