VOL. 6, NO. 3, MARCH 2011 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

ULTRA-SHORT LASER PULSE INTERACTION WITH NICKEL FILMS

E. Annan[1] and H. V. Snelling[2]
[1]Department of Materials Science and Engineering, University of Ghana, Accra, Ghana
[2]Department of Physics, University of Hull, United Kingdom
E-Mail: ebenk45@yahoo.com

ABSTRACT

Laser induced forward transfer method involves three sequence of events (i) laser pulse heats up the front surface of the film until it melts (ii) the melt front propagates through the film until it reaches the back surface and finally (iii) at or close to melt-through the metal vapour pressure at the front propels the molten film to the substrate. Many authors have shown potentials of this method in direct writing and photo-mask repair. In this paper, laser induced forward technique is applied to nickel films of thicknesses 98nm, 200nm and 322nm by using Ti: Sapphire femtosecond laser. Threshold energies for both direct and backside ablations are calculated. The feasibility of the transfer process is also demonstrated on nickel film on silicon wafer. Elevated features observed on some films during transfer process have been explained.

Keywords: Ultra-short pulse laser ablations, nickel film, lift technique, femtosecond ablation, backside ablation.

INTRODUCTION

Ultra-short pulse lasers have been shown to hold great potential for high-precision micro-machining. The pulse widths of these lasers are in the order of femto-seconds (10^{-15} s) and sub-Pico second regime. The extremely short duration of a femto-second pulse highly limits heat diffusion, resulting in a clean and almost defect-free ablation, making high precision micro-machining achievable [1]. Sub-micrometre features have been shown to be attainable using ultra-short pulses [1]. Other admirable advantages of using ultra-short pulses are significant reduction or complete removal of heat affected zone (HAZ) and as a result, improvement of the contour sharpness for laser-processed structure [2, 3]. These advantages of femtosecond lasers have led to a challenging phase of application research. Valuable applications, for instance fabrication of binary photo-masks [4] and their repair [5] are of paramount importance.

The idea of using ultra-short laser pulse for sub-micron feature machining was first demonstrated by Pronko [9] in 1995. With a 6 micron laser spot, he produced a 300nm-diameter hole on gold film which was irradiated by fluence as low as 40 nJ. Later the mechanism behind the sub-spot size machining was explained by Liu [10] and made a cut 300 nm-wide groove on nickel film with a spot size of 1.7 microns in diameter [11]. Film thickness and thermal diffusion length has been found to have a relation that assists in understanding the mechanism during ultrshort pulse micro-machining. When the metal film thickness, is greater than diffusion Length, L, the fluence for ablation is independent of film thickness. This is explained by a simple thermal model based on the fact that in the nanosecond pulse regime, the critical energy density required for melting or vaporization is given by E = F/L_{th}, where F is fluence and L_{th} is the thermal diffusion length [8].

In 1986, Bohandy *et al.*, [13] reported a new laser-film transfer technique with a ns pulse duration of 193nm. This method of transfer is known as the laser-induced forward transfer (LIFT). From their model, the LIFT consist of this three sequence of events (i) laser pulse heats up the front surface of the film until it melts (ii) the melt front propagates through the film until it reaches the back surface and finally (iii) at or close to melt-through the metal vapour pressure at the front propels the molten film to the substrate.

In reference [13] potency of the method for direct writing of metal features for copper film supported on an optically transparent substrate using a single pulse of excimer is shown. This was followed with success in transferring copper and silver thin films unto fused silica with 532nm frequency doubled YAG laser [14]. Since then many investigations have be done with different lasers for various range of metals [1-4 and 14]. The LIFT mechanism of YbaCuO and BiSrCaCuO high T_C thin film irradiated by a single pulse ArF excimer; 20ns pulse duration was investigated by Fogarassy [18]. Adrian *et al.*, [19] calculated the temperature distribution in the thin film during the laser heating using calculus of finite difference. They then strongly suggested that the pressure generated in the film-substrate interface being reasonable for film removal. Almost same mechanism was proposed by Schultlze *et al.*, [20] at lower laser intensities for thin films and at higher intensities for thick films. At lower intensities, the thin film is melted and blown off by the pressure generated at the film support/substrate interface. In the case of thick film, the film is explosively blown off due to the high evaporation pressure at the interface because of the overheating of the phase or burst solid phase

In experimental tasks, the set-up needs to be optimized. Sano *et al.*, [15], which employed laser induce forward transfer (LIFT) on Au and Ni thin films using 193nm excimer 30ns pulse duration, optimized their system in reference [16] with regard to film-acceptor distance and choice of fluence. It should be noted that in all these work the laser induce forward technique, has shown the ability for direct writing metals for interconnects and mask repair and also simple dielectric materials such as metal oxides [5, 14, 17].

Table-1. Nickel thermal constants.

Constants	Nickel metal solid
Thermal Conductivity	(300 K) 90.9 $W \cdot m^{-1} \cdot K^{-1}$
Specific heat capacity	(25 °C) 26.07 $J \cdot mol^{-1} \cdot K^{-1}$
Density	8.908 $g \cdot cm^{-3}$
Heat of fusion	17.48 $kJ \cdot mol^{-1}$
Heat of vaporization	377.5 $kJ \cdot mol^{-1}$

The melting and boiling points are found to be 1728 K and 3186 K, respectively.

EXPERIMENTS

Sample preparation

A physical deposition method: sputtering of thin film preparation was adopted. In sputtering, energetic ions (example Ar^{+}) strike a target consisting of the material to be deposited. As a result of the interaction, a continuous flux particle is produced. The emitted atoms condense on a substrate to form a film. The ions are usually extracted from plasma which is sustained by a direct current (D.C) voltage, RF power or with the help of magnetron.

Table-2. Film preparation times and applied volts.

Film thickness	Time/mins	Voltage/V
Film A (98nm)	5.0	150.0
Film B (200nm)	6.0	110.0
Film C (322nm)	4.0	90.0

The Transfer

A schematic diagram is shown in Figure-1 demonstrating the main steps involved in laser induced forward transfer technique: laser ablation, detaching of film and final deposition on a substrate. The laser irradiation source was Ti: Sapphire CPA ultra-short laser of 800nm wavelength and pulse duration of 3.7ps. The laser beam was focused with an objective 10X microscopic lens of focal length 3.5mm. The numerical aperture of the lens was 0.25. Neutral density (ND) filters was used for power reduction from 60mW to 5mW at a repetition rate of 1 KHz.

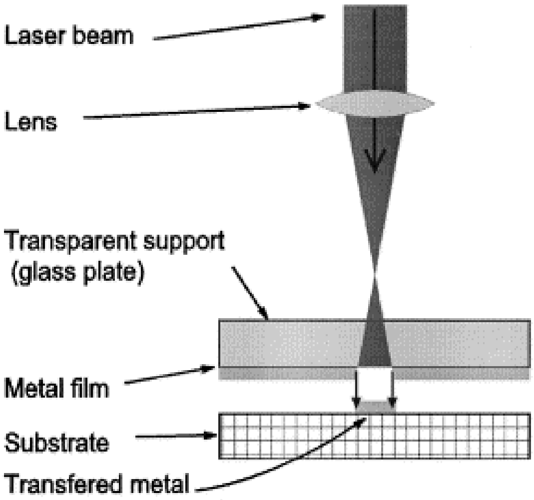

Figure-1. Schematic diagram of laser induced forward transfer technique (LIFT).

Target and substrate were mounted together on an aerotech motion controlled X-Y-Z translation stage. This experiment was performed in air on the target 322nm nickel film. The acceptor substrate was silicon wafer (thickness 0.36mm) was attached at the other side. At z = -4.9mm of the aerotech translation stage, irradiation of the target was executed with a reduced transmitted power of 5mW. Notice that irradiation was manually triggered for single pulse emission. At this transmitted power, elevated spots were seen on film.

Figure-2 and Figure-3 show elevated spots of 25μm and 40μm separation of any two spots at feedrates 800mm/min and 1000mm/min, respectively. Note that these elevated spots were observed at lower microscopic powers. With the exception of fluence (energy per unit area), beam characteristics of the Ti:Sapphire used in producing elevated features in Figure-3 were adopted for the transfer process.

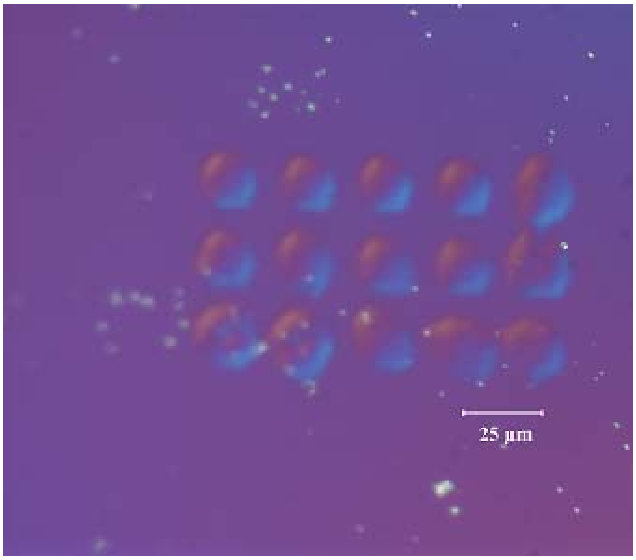

Figure-2. Elevated spots after beam irradiation at feedrate of 800mm/min.

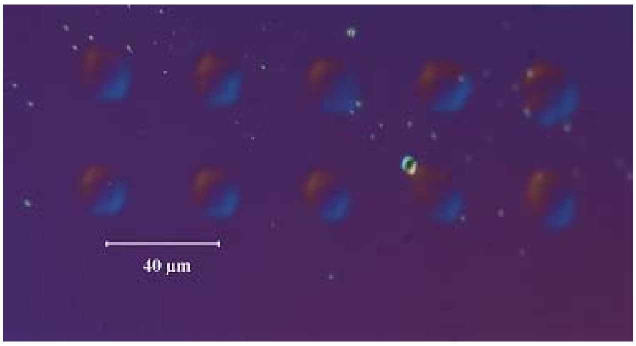

Figure-3. Elevated spots after beam irradiation at a feedrate of 1000mm/min.

RESULTS AND DISCUSSIONS

During irradiation of the laser pulse, energy is deposited in the laser spot-size and within the thermal penetration depth of the electrons at the support-film interface. In the ultra-short pulses, the peak power density is too high and the time scale too short that the electrons and the phonons are not in equilibrium. With few nanometers of penetration depth, energy is in a small volume and therefore very high peak power or energy density affecting the smaller volume. The material within the penetration depth reaches vapour phase without experiencing melting phase. It is important to note that only the material at the metal glass interface reaches a superheated matter. The increase in temperature is so fast that, only the material within the penetration depth is affected. Thermal diffusivity and optical absorption length calculation using Table-1 data confirms the dominant process for the pulse regime.

Table-3. Threshold ablation energies for different film thicknesses.

Film thickness (nm)	**Threshold ablation**	
	Direct ablation (µm)	**Backside ablation** (µm)
98.0	0.03	0.37
200.0	0.05	3.05
322.0	2.49	4.55

In laser induced forward transfer process as already stated energy absorbed at the interface is thought to generate a high pressure, the targeted area of the film is detached by the intense pressure and is transferred, and finally the detached material arrives at the acceptor substrate and is deposited. This process is highly appropriate to be applied in high precision micro-electronics/photonic devices. Patterning is also achieved by moving the laser beam (or substrate) or by pattern projection.

In the case of ultra-short pulses, since the pulse width is too short for heat to be conducted away from the area of focus, the deposited energy is within a shallow layer at the material surface. The highly concentrated energy heats the material quickly past the melting phase to the vapour phase. Thus the material is directly vapourised away from the surface dramatically reducing the spread of melt. Hence the heat of diffusion is greatly reduced. This thermal diffusion length is estimated theoretically to be approximately 2nm. It must be noted that material removal is accomplished through the melt expulsion driven by the vapour pressure and recoil of the light pressure as said earlier, in the case of longer pulses.

Figure-4 and Figure-5 show feasibility of the transfer process. Interesting features-elevated spots are observed in Figures 2 and 3. These elevated spots are as a result of ablated energies that were below the threshold energies. Threshold energies are known to be the minimum energies required to eject or detach a pattern from it parent film. The results of the present work with regard to the threshold energies calculated Table-3 for both direct and backside ablations confirm this. It is relevant to state that if this ‘elevated spots’ can be maintain they will find usefulness in diffractive optics. However, efforts to maintain their properties failed as bumps collapse gradually over two weeks.

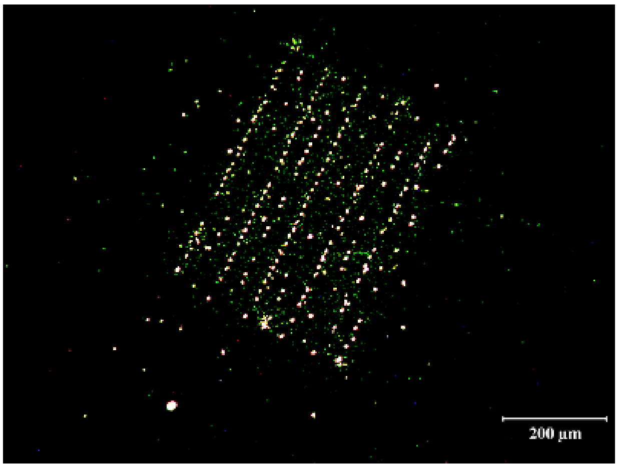

Figure-4. Deposited film on silicon wafer at lower microscopic power.

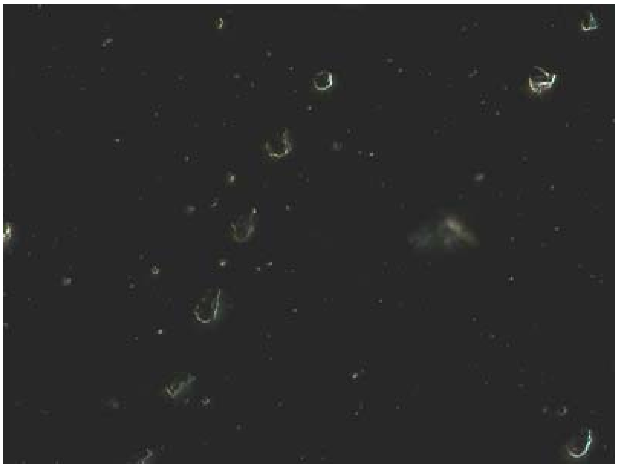

Figure-5. Deposited film on silicon wafer at higher microscopic power.

CONCLUSIONS

In laser ablation experiments, an idea of the type of process (either photo-chemical or thermal processes) can be known by estimating thermal diffusion length and optical absorption depths. The parameter with greater value dominates. In the case of KrF (13ns pulse duration), thermal diffusion length is greater than the optical absorption length, a thermal 1- dimensional equation was adopted to calculate surface temperature, and vapour pressure. In shear stress analysis we considered two forces: vapour force and that from shear stress of the film. In excimer laser transfer technique it is important to possibly melting regime as adhered by Sano *et al*., [6]. Melting effects were observed around 0.58 Jcm^{-2} resulting in surface contraction seen starting at the circumference of the circular image in a spiral form towards the centre of the irradiated spot.

In an attempt to ascertain the minimum energy for the transfer process, direct and backside ablation was undertaken. The results confirmed literature proven thresholds energies of direct ablation being less than that of backside ablation.

It must be on record that the feasibility of the laser induced forward transfer has been demonstrated. The laser induced forward transfer performed on 322nm Nickel film showed interesting results at different feedrates. First, more scattering of particle were observed at a higher feedrate of 1000mm/min as compared to fewer spatters at 800mm/min. Both transfers executed at 1000 Hertz of frequency. Secondly, irradiated spots with energies less than threshold value resulted in film having bumps. For better adhesion of deposited material on acceptor substrate, optimization of the film-acceptor distance and good choice of fluence are essential.

RECOMMENDATIONS

We concluded on a number of important areas. One of such areas has to do with film-acceptor substrate. The significance of film-acceptor distance has been demonstrated [13] and could be further experimented for other films. I will therefore recommend further work to be done on optimization of the system for better transfer.

Another area has to do with surface morphology of transferred film. Scanning electron microscopic images could be taken to ascertain the level of degradation of the supporting substrate and disposition spread of the film. In other words it is important to know the particle distribution of the deposited film. The uniformity of the deposited film cannot be entertained in micro-electronic applications, mask repair and others. It is also recommended that substrate damage should not be entertained during the LIFT technique. The precision of energy for backside ablation is relevant.

Finally, elevated surfaces of irradiated spots called bumps were observed for threshold energies less than the minimum threshold value. Investigations; both theoretical and experimental should be done in the possibility of sustaining the bumps. It usage in diffractive optics will be novel inception.

REFERENCES

[1] K. Venkatakrishnan *et al*. 2002. Optics and Laser Technology. 34: 575-578.

[2] M. Meunier *et al*. 2003. Processing of metals and semiconductors. SPIE USE. 6: 4978-5032 .

[3] N. H. Rizvi. 2002. Riken Review Number 50. Focussed on Laser Precision Micro-fabrication.

[4] K. Venkatakrishnan *et al*. 2002. J. of Micromechanics Micro-Engineering. 12:775-779.

[5] R. Haight *et al*. 1999. Journal Vacuum Science. Technololgy B. 17(6).

[6] S. Preuss *et al*.1994. Applied Physics A. 59: 79-82.

[7] E. Mathias *et al*. 1994. Applied Physics A. 58 :129-136.

[8] M. Womack *et al*. 2004. Applied Surface Science. 221 : 99-109.

[9] Pronko P *et al*. 1995. Machining of submicron holes using a femtosecond laser at 800nm. Opt. Commun. 114: 106-110.

[10] X. Liu, 1998. Technical Digest-conference on Lasers and Electro-Optics. p. 511.

[11] J. Bohandy *et al*. 1986. Journal of Applied Physics. 60(4): 1538.

[12] J. Bohandy *et al*. 1988. Journal of Applied Physics. 63(4): 1158.

[13] X.Liu *et al*. 1997. IEEE J. Quantum Electronics. 33: 1706-1716.

[14] Z. Kantor and T. Szorenyi. 1995. J. Applied Physics. 78: 2775.

[15] T. Sano *et al*. 2002. Applied Surface. 197 : 411-415.

[16] T. Sano *et al*. 2003. Applied Surface Science. 186: 221-226.

[17] I. Zergiote *et al*. 1998. Applied Physics A. 66 : 579

[18] E. Forgarassy. 1990. Proc. SPIE 1394. p. 169.

[19] F. Adrian *et al*. 1997. Journal of Vacuum Science Technology. B5, 2370.

[20] V. Schultze and M. Wagner. 1991. Applied Physics A. 53: 241.