Title

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Abstract

A compact apparatus is developed for deposition of metal thin film. The system employs an RF discharge plasma source with a straight RF antenna, which is made of or covered with deposition material, serving as sputtering target at the same time. The average deposition rate of copper thin film is as high as 450nm/min. By properly allocating the metal materials on the sputtering antenna, mixture deposition of multiple metal species is achieved. Using an ion beam imprinting scheme also taking advantage of ion beam focusing technique, two different schemes of direct patterning deposition process are developed: direct depositing patterned metallic thin film and resistless ion beam sputter patterning. Preliminary experiments have demonstrated direct pattern transfer from a template with feature size of micro scale; patterns with more than 10x reduction are achieved by sputtering patterning method.

I INTRODUCTION

Sputtering deposition method has been applied to various fields of manufacturing industry. In particular, this thin film formation method has become very important for the fabrication of electric and optical devices. In addition, high rate sputtering methods for ferromagnetic materials, such as Fe and Ni, have been developed expending further the fields of sputtering application.[1-2] Some prior research has shown that if the sputtered atoms are highly ionized, it will be very useful to control the film properties by the aids of the ionic charge and/or the kinetic energy of the ionized sputtered atom.[3-5] High ionization rate of the sputtered atom is a very important requirement in directional sputter deposition which is often used in high aspect ratio deposition applications[6].

Based on this consideration, people modified the magnetron sputtering system by adding a high-frequency (HF) coil in between the sputtering target and the substrate holder, using the HF discharged plasma to ionize the neutral sputtered atoms. The compact sputtering system built at Lawrence Berkeley National Laboratory combines the sputtering target and the HF discharge unit together, and can perform highly-ionized deposition in an efficient way.

In some particular applications, deposition on curved substrates is required, such as cylindrical tubes. The Plasma and Ion Source Technology Group developed a deposition method for this kind of application few years ago[7]. In this method, a movable antenna driven by an electric motor moves in and out continuously inside the source tube. The material sputtered from the antenna deposits on the inner surface of the tube uniformly. But it is necessary to control the movement of antenna precisely, and the inner diameter of the tube will be limited by the size of the antenna coil. Compared with the prior deposition method, some improvements have been achieved by the new method. Both the source design and deposition process are simpler, and coating of the inner surface of small tubes is feasible.

Besides forming thin films of single metallic specie, mixture deposition of multiple metal species has found more and more important applications especially in the field of magnetic storage media formation. By allocating the depositing materials in a proper way the compact sputtering system can accomplish this task very well. Some preliminary experiments have been performed for mixture deposition of Ni and Fe alloy.

Conventionally a patterned thin film is fabricated after going through a series of processes: deposition, lithography, and etching. The focused ion beam technology makes it possible to direct pattern the metal thin film. Two kinds of patterning scheme are developed Some preliminary results using these methods have been achieved and the experiment will be explained in details in the following discussions.

Π. PLASMA SOURCE AND OPERATION

An RF-discharge plasma source has been developed for deposition of metal thin film. The schematic of the source is shown in Fig 1, the source body is made of a piece of cylindrical shaped copper. A circular opening is made in the middle and it is enclosed by the substrate to be deposited. A straight thin copper tubing goes all the way through in the axial direction acting as internal antenna. Water flows inside the antenna for cooling purpose. The advantage of this configuration is that one can not only do deposition on a planar surface but also coat inner surfaces of cylindrical-shaped sample targets by installing the target tubing coaxially with the straight antenna. Such a system can accommodate a wide range of sample size, short or long, large or small. The two leads of the straight antenna are connected to a 13.56 MHz RF power supply through a matching network. The metal material to be deposited is assembled as part of the RF antenna. The source has a quite flexible requirement on the configuration of the sputtering target. Tubing, rod and metal foil can all be assembled easily. Thus thin films of most of the metallic species in the periodic table can be deposited using this source. Argon is introduced into the source chamber to generate plasma. It has relatively high atomic mass, and is chemically stable so that it won't react with the metal materials during the sputtering process. Permanent magnets are installed on the outer surface of the source body, the magnetic field generated by the permanent magnets will confine electrons from being lost, thus help to ignite and maintain high-density plasma. The deposition substrate sitting on a copper sample holder is assembled facing the opening area of the plasma source. The source body is electrically grounded firmly, to ensure the thin film grow sturdily on the substrate.

To ignite plasma, relatively high pressure of argon gas is needed. Under 450w forward RF power, plasma with a relatively low density appears first due to capacitive coupling. When the gas pressure keeps increasing, the plasma density becomes higher and higher. At hundreds of mTorr gas pressure, the plasma jumps into a high-density mode. At the same time, the RF antenna will serve as a sputtering target. The argon ions in the plasma sheath, driven onto the antenna surface by the voltage fluctuations on the RF antenna, sputter off the metal material on the antenna. Usually the voltage fluctuation on the RF antenna is about couple kilovolts; it's about the typical bias voltage used in conventional sputter magnetron. Thus no extra high voltage bias in needed in this system. The metallic atoms sputtered from the antenna will diffuse in the plasma. Since the ionization potential for most metal species is lower (e.g. 6~7 eV) than argon (15.8 eV), the metal atoms are easily ionized in the high density argon plasma. A change in color of the plasma is easily observed from a quartz tube extending out from the source. The high metallic ion to neutral ratio results in improved thin film quality[3].

III. MIXTURE DEPOSITION AND DIRECT PATTERNING

1) Mixture deposition

Based on the setup described above, thin films of different metal species are deposited on substrates of silicon, glass, copper and stainless steel. Metallic species of Cu, Fe, Ni and Pd have been tested. Sturdy and uniform thin films are achieved. A layer of copper thin film formed with high uniformity is shown in Fig 2, the average deposition rate is about 450nm/min at a cw RF power of 500w. It varies for different metal materials due to different sputtering yields. Also the deposition rate and deposition uniformity strongly depend on gas pressure and RF power, which has been investigated by many other researchers, and experimental testing is still in progress to optimize the parameters. Mixture deposition of different metal species is accomplished by arranging the antenna alternately with small pieces of different metal materials as shown on Fig 1. When each piece of material is small enough and arranged uniformly on the antenna, the deposited mixture is also fairly uniform. Mixture deposition of Ni and Fe is carried out, and the TOF-secondary ion mass spectrum (SIMS) analysis results are shown in Fig.3. The distribution of both Fe and Ni are uniform, and the ratio of the two species in the alloy thin film is about 33.7: 66.3. Almost no argon is detected in the coated layer. By changing the proportion of exposure area of the metal species on the antenna and taking into account the difference of sputtering yields, the ratio of each deposition composition is adjustable. NiFe films are very important soft magnetic materials due to the high magnetic moment and low magnetostriction. The capability of depositing NiFe alloys with adjustable compositions will allow a large number of parameters available for material characteristic modification such as dielectric constant and magnetic coercivity of the nanoscale islands, which makes the technique very useful in magnetic recording media fabrication[8].

2) Direct patterning

Conventionally, in semiconductor industry, metallic thin film is patterned using a light-sensitive photoresist and etched using reactive ion etching (RIE) to form circuit elements. The pattern generation process is usually an extremely slow process and costs a lot. Taking advantages of focused ion beam technology and combining with an ion beam imprinting scheme[9], two different metal thin film patterning schemes are developed. One is called directly depositing patterned metallic thin film and the other one is resistless ion beam sputtering. In the first scheme, a stencil mask containing apertures with different shapes like lines, squares and round holes is used as the plasma electrode. The metal ion beam comes out through the mask, reaching the substrate in similar shapes. By controlling the distance of the gap and the electric field between the mask and the substrate, the demagnifications of patterns can be adjusted. In this way, some special patterns can be formed at one shot instead of scanning a small round beam for a long time. The patterning process thus can be simplified a lot.

Contact deposition is tested first. In this case, the mask and the substrate surface contact firmly. Both the source body and the substrate are well grounded. Metallic ions reach the surface of the substrate with the energy equal to the plasma potential. 1:1 pattern transfer is achieved under this condition and some deposited patterns are shown in Fig 4 and the step height analysis results by KLA-TENCOR ALPHA ASIQ profiler are shown on the right. At micro scale, contact pattern transfer can work fairly well. However, it still has a strict requirement on a firm contact between the mask and the sample surface and also on the flatness of the mask. Moreover, it can only conduct 1:1 pattern transfer and cannot produce any reduction.

Focused ion beam technology can help to solve these issues. In a proof-of-principle experiment, the substrate is biased at a negative potential relative to the ground; an electric field is generated between the plasma electrode (the mask) and the substrate. The voltage applied is 100-200eV to ensure deposition effect dominates instead of sputtering or doping. Metal ions are extracted and reach the substrate with a demagnification factor of about 2. A low energy beam focusing system will be required in future.

But in some cases, when the substrate is an insulating material, biasing on the substrate will make surface charging an important issue. Multiple beam writing will make it even more difficult for surface neutralization. A double-chamber source configuration is developed to resolve this issue[10]. The source is shown in Fig 5 (a), with the carefully designed beam column (shown in Fig 5 (b)), a combined electron and focused ion beam can be generated. Surface charging issue can be eliminated completely. Using the configuration shown in Fig 5 (c), multiple beam surface neutralization can also be achieved[10].

In the second scheme of resistless ion beam sputtering, a layer of thin film is deposited first, and then different shapes of features are formed by a shaped Ar^+ argon beam with certain energy and beam spot size. With a beam focusing electrostatic lens, the ion beam can be focused to hundreds or tens nanometer scale, which will make this direct pattern technique useful in the application of photomask fabrication and repair. Some preliminary experiments have been done. In the experiment, a single-gap extraction configuration is employed. The argon beam extracting from 250µm diameter holes which is focused by the electric field between the mask and the substrate, is used to sputter a Ni thin film coated on a piece of silicon wafer. As shown in Fig 6, a circular area with a diameter of 20µm on the thin film is totally sputtered off which indicates that a demagnification factor of 12 is achieved. The measured profile is shown on the right.

IV SUMMARY

High quality and uniform metal thin film deposition of both single element and multiple elements have been achieved. Two schemes of direct patterning of metallic thin film have been demonstrated: direct depositing patterned metallic thin film, and resistless ion beam sputtering. They simplify pattern generation process design and improve the throughput by greatly reducing beam scanning time.

But to push them into real applications, well-defined beam profile and beam spot size are very essential. A computer simulation using Munro code is being carried out to aid in designing the electrostatic lens for this direct patterning deposition system. At the same time tests are still going on to find out the optimum source operation parameters.

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Figure Captions:

Figure 1 Schematic of the ion source for metallic ion sputtering deposition

Figure 2: Image of copper thin film deposited on silicon substrate taken by laser interference microscope (left) and profile (right)

Figure 3: Directly patterned copper deposition: pictures taken under optical microscope (left), step height analysis results by KLA-TENCOR ALPHA ASIQ profiler (right).

Figure 4: TOF-SIMS analysis result of the patterned NiFe alloy thin film: Ni in the thin film (left), Fe in the thin film (middle), square shaped thin film patterns on silicon substrate (right).

Figure 5: (a) Double chamber source developed at Lawrence Berkeley National Laboratory for combined electron and focused ion beam generation; (b) 3D simulation design of beam column; (c) Schematic of multiple combined beam generation.

Figure 6: Resistless argon beam sputtering Ni from silicon substrate: pictures taken under optical microscope (left), step height analysis results by KLA-TENCOR ALPHA ASIQ profiler (right).

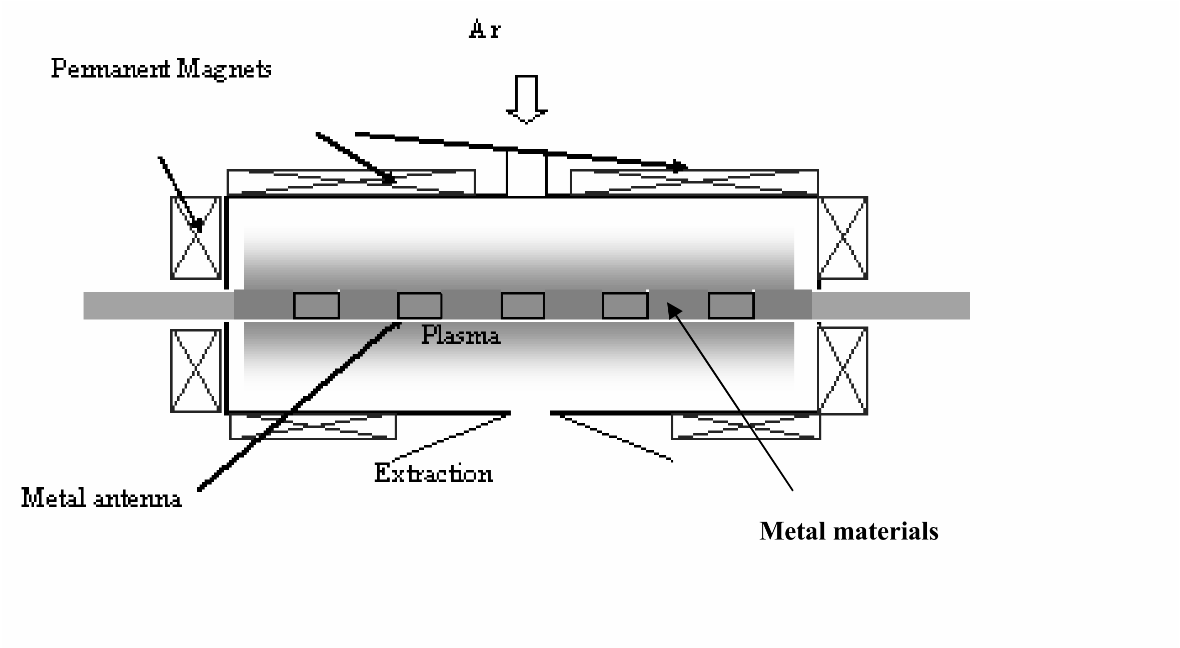

Ar
Permanent Magnets
Plasma
Extraction
Metal antenna
Metal materials

Figure 1

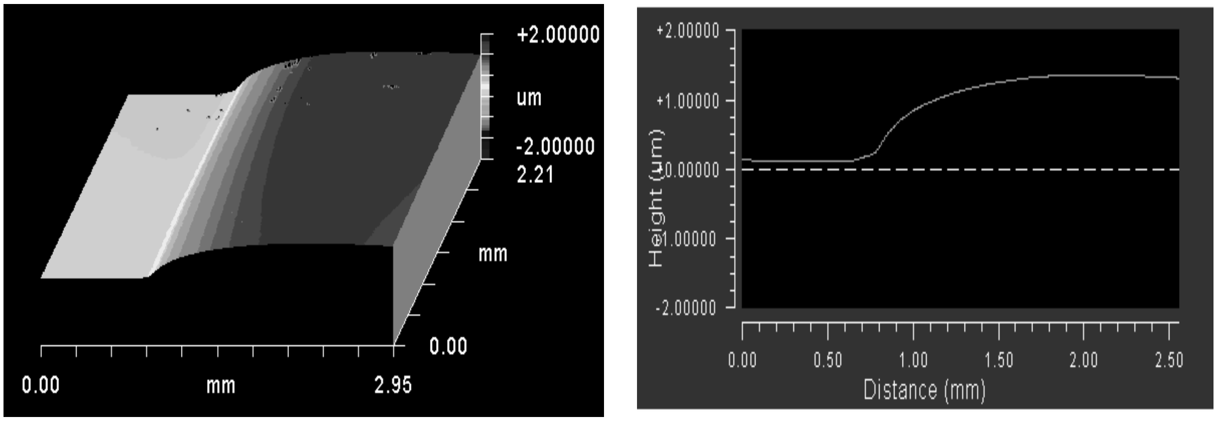

+2.00000
um
-2.00000
2.21
mm
0.00
0.00
mm
2.95
+2.00000
+1.00000
0.00000
-1.00000
-2.00000
Height (um)
0.00
0.50
1.00
1.50
2.00
2.50
Distance (mm)

Figure 2

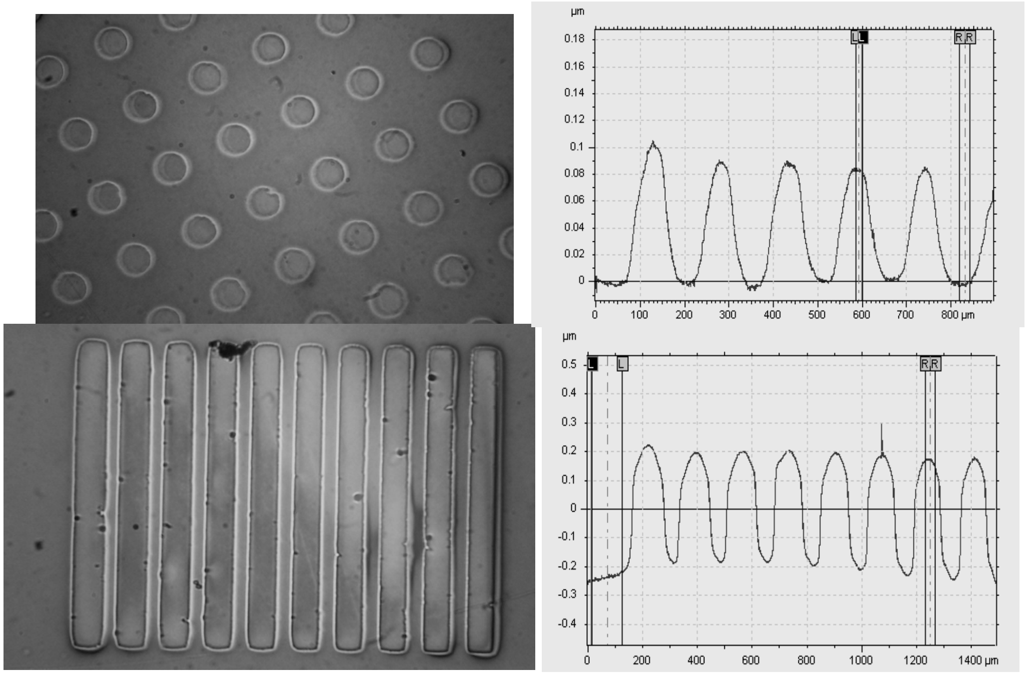
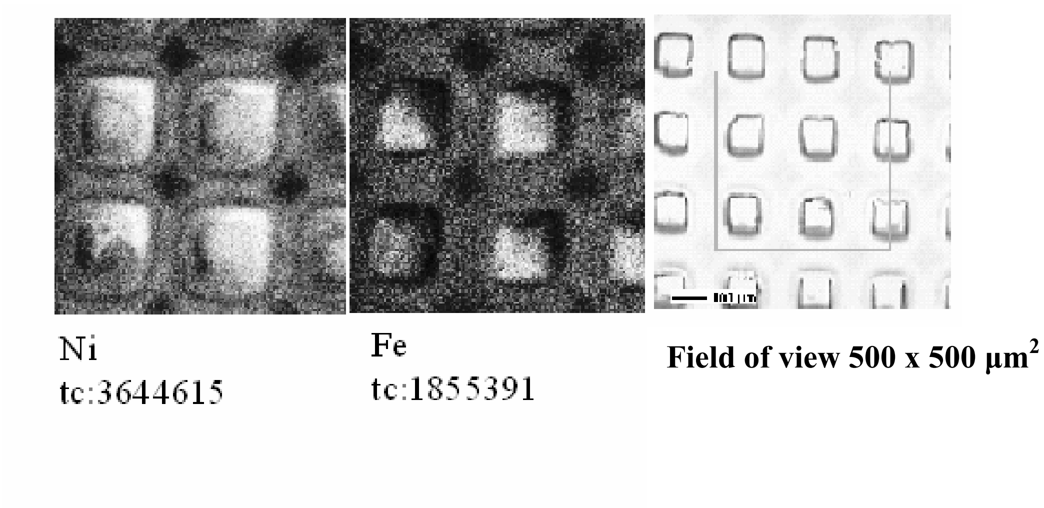

µm
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
L
R
0
100
200
300
400
500
600
700
800 µm
µm
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
L
R
0
200
400
600
800
1000
1200
1400 µm

Figure 3

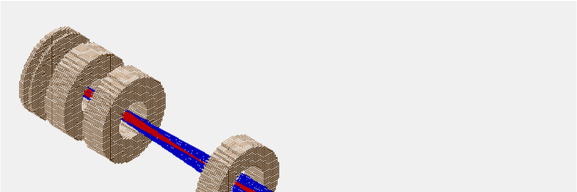


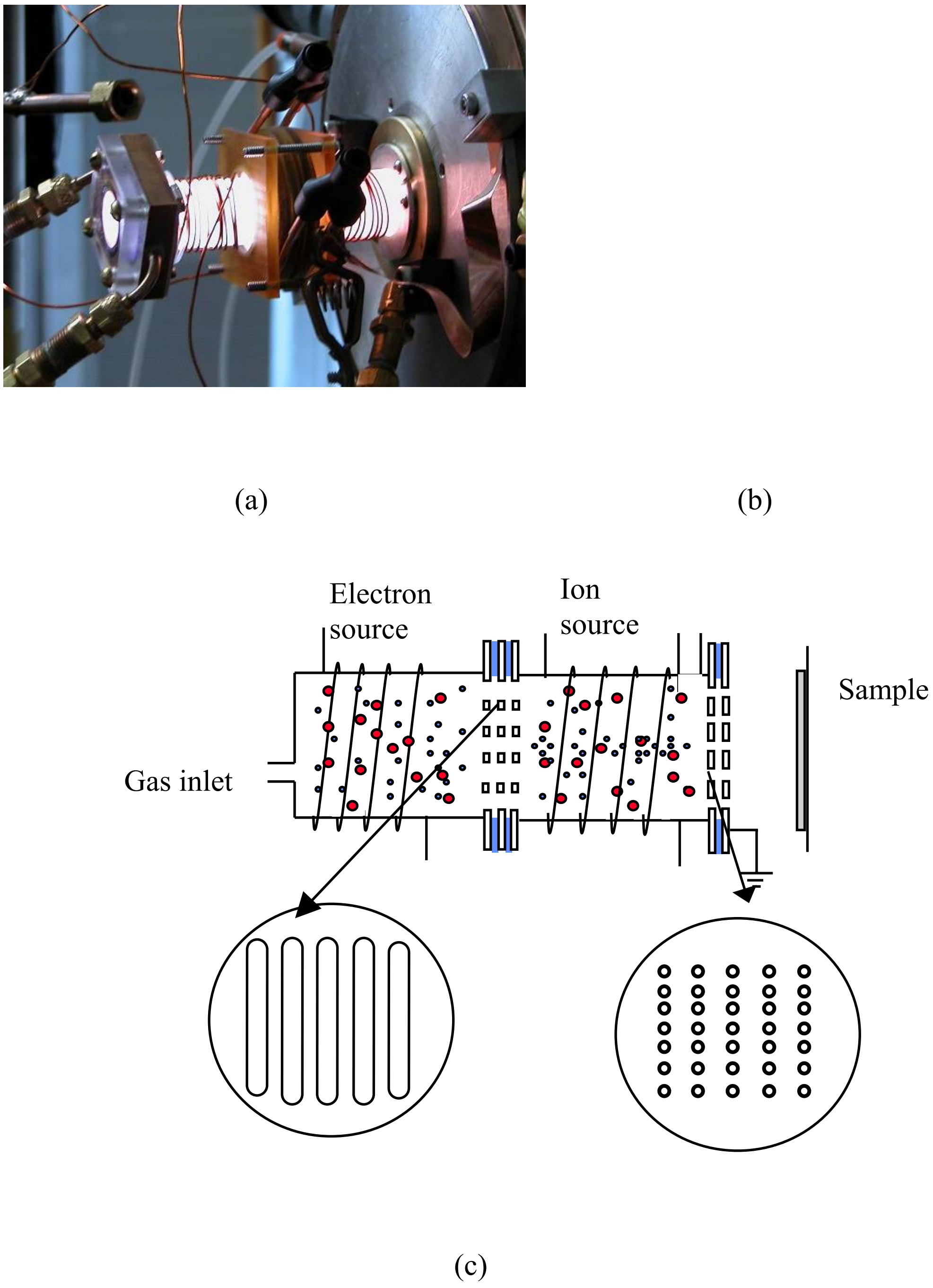
Ni
tc:3644615

Fe
tc:1855391

Field of view 500 x 500 μm^2

Figure 4





(a) (b)

(c)

Figure 5

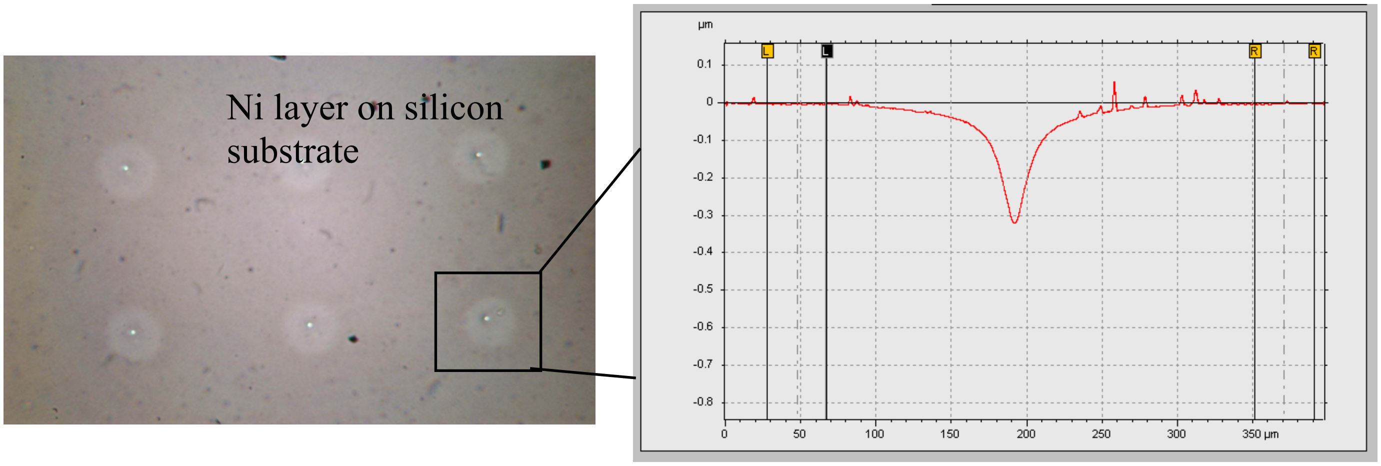

Ni layer on silicon substrate
µm
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
0
50
100
150
200
250
300
350 µm
L
L
R
R

Figure 6