A Dependence of Sputtering Rate On Primary Ion Energy In Sputter Depth Profiling*

—— How to control the sputtering rate in depth profiling

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In this paper, a mathematical relationship of sputtering rate and primary ion energy for ion sputtering in depth profiling has been given and confirmed on GaAs, AlGaAs, and Si samples experimentally. This relationship give helpful directions on selecting the experimental parameters in sputter depth profiling.

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INTRODUCTION Different sputtering rates are usually required in a sputter depth profiling analysis. When the primary ion energy changes, the sputtering rate will make a corresponding change. The change in the sputtering rate not only related with the sputtering yield, it is also determined by the change in the sweeping area of the primary ion beam for the equal beam current[1,2,3]. This relationship may be different on different type of instruments. In literature, the sputtering rates of some kinds of samples with different primary ion have been measured. But this measurement is limited with the special requirements of experiment. With the development of research work, the theoretical relationship between sputtering rate and experimental parameters is needed to be found out in order to control the sputtering rate. In this paper, a relationship between the sputtering rate and the *primary ion energy in sputter depth profiling has been studied.*

THEORETICAL ESTIMATION On PHI 610 SAM with a differential ion gun and MIQ-156 type SIMS instrument in my Lab., a primary ion beam is provided by an ion gun and the sweeping voltages of an well focused ion beam are applied on two sets of reflection plates. The sweeping area is controlled by a magnification control knob.

The sputtering rate of the primary ion beam on a sample, $\dot{Z}$ (normalized with the ion beam intensity) as a function of E_p is content with the following formulation[1] [2] [3]:

$$\dot{Z} = k\frac{S(E_p)}{A} \quad (1)$$

where $S(E_p)$ is the sputtering yield, which is a parameter related with the primary ion beam energy (E_p); A is the sweeping area of the primary ion beam; k is a constant.

From the basic principles of physics, we can give:

$$E_p = \frac{1}{2}mu_p^2 \quad (2)$$

where m is the mass of the primary ion, u_p is the ion velocity.

Assuming a primary ion of electric charge q passes through an uniform electronic deflection field with a length of l, and a field intensity of ε, we know the acceleration is $\frac{\varepsilon q}{m}$, the passing time is $\frac{l}{u_p}$, then we have:

$$u = \frac{\varepsilon q}{m} \cdot \frac{l}{u_p} \quad (3)$$

where u is the lateral velocity of the ion after passing through the deflection field.

From Eq.(2) and Eq.(3) we obtained:

$$\frac{u}{u_p} = \frac{ql}{2} \cdot \frac{\varepsilon}{E_p} \propto \frac{\varepsilon}{E_p} \propto \frac{V}{E_p} \quad (4)$$

where V is the voltage applied across the deflection plates.

There are two pairs of deflection plates that enable the primary ion beam to sweep at two perpendicular directions. Let V_1 and V_2 be the sweeping voltage on the two sets of plates respectively, and let u_1 and u_2 be the maximum lateral velocity of the ion after passing through the deflection field. We know $A \propto (\frac{u_1}{u_p}) \cdot (\frac{u_2}{u_p})$. From Eq.(4) we have:

$$A \propto \frac{V_1 V_2}{E_p^2} \quad (5)$$

$$\therefore \quad \dot{Z} \propto \frac{S(E_p) \cdot E_p^2}{V_1 V_2} \quad (6)$$

This is the relation of the sputtering rate. It can be seen that $\dot{Z}$ (A/mA.min.) is proportional to the square of the primary ion energy E_p, and is inverse proportional to the product of the two sweeping voltages.

Let $f_i \propto 1/v_1v_2$(i =1, 2, 3, 4, corresponding to the 1st, 2nd, 3rd and 4th control knob position respectively), when the change in sputtering yield for a certain material is not significant(for Si, see [2]), relation (6) can be expressed as:

$$\dot{Z} \propto f_i \cdot E_p^2 \qquad (7)$$

Set the magnification control knob at the commonly used 1st, 2nd, 3rd and 4th position, taking a measure of the sweeping voltages, then the ratio value of $1/v_1v_2$ (f_i) will be obtained, then the relationship between sputtering rate and the primary ion energy will be decided. If the sputtering rate corresponding to primary ion energy E_{p0} and the knob position i_0 is known as $\dot{Z}_0$, the sputtering rate $\dot{Z}_i$ corresponding to primary ion energy E_p and knob position i can be obtained from relation (7):

$$\dot{Z}_i = \frac{f_i}{f_{i0}} \cdot \frac{E_p^2}{E_{p0}^2} \dot{Z}_0 \qquad (8)$$

Knowing a measured sputtering rate, the unknown sputtering rates can be estimated using the formula (8) above, when the primary ion energy and the sweeping area are selected.

EXPERIMENTAL CONFIRMATION The formula(8) has been confirmed in SIMS depth profiling, on our Riber MIQ-156 type secondary ion mass spectrometer. The experimental sputtering rates were measured by the sputtered crater depths and sputtering time. The theoretical sputtering rates were calculated from relation (8). The measured sputtering rate with E_{p0}=10keV and i=3 was used as $\dot{Z}_0$ in the calculation. The result is shown in Table 1. It can be seen the calculated sputtering rates are in consistent well with the measured ones in table 1. Generally, the maximum error is less than 20%, and the average error is less than 10%.

The depth profiles of an Si ion implanted sample of GaAs obtained under different experimental conditions are shown in Fig.1. The sputtering rates of Fig.1 have been calculated from formula (8). It can been seen that the obtained projected ranges of different depth profiles coincide each other. So with the knowledge of dependence of the sputtering rate change up to other experimental parameters, it is sure that depth profiling can be made under the same sputtering rate and the same sputtering area with the adjustment of the experimental parameters.

The formula (8) would be valid for Auger depth profiling as well. The experimental confirmation is still in process.

CONCLUSIONS In this study, a mathematical relationship between sputtering rate and primary ion energy in sputter depth profiling has been given and confirmed in SIMS depth profiling experimentally. These are very useful in sputter depth profiling.

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Table 1. The dependence of the sputtering rate on the primary ion energy and the sweeping area [a] :

(I), O_2^+ ion source, GaAs sample:

Ep (keV)	Knob Position	$\dot{Z}_{Cal}$ (Å/μA·min)	$\dot{Z}_{Mea}$ (Å/μA·min)	Error (($\dot{Z}_{Mea}$-$\dot{Z}_{Cal}$)/ $\dot{Z}_{Cal}$*100%)	Average Error (%)
6	3	1797.3	1670.6	-7.0	
8	3	3195.2	3573.6	11.8	
10	1	216.1	224.7	4.0	6.2
	2	1383.2	1368.8	1.0	
	3	4992.5	4992.5	0	
	4	19408.1	16006.4	-17.5	
12	3	7189.2	7320.6	1.8	

(II), O_2^+ source, $Al_{0.3}Ga_{0.7}As$ sample:

Ep (keV)	Knob Position	$\dot{Z}_{Cal}$ (Å/μA·min)	$\dot{Z}_{Mea}$ (Å/μA·min)	Error (($\dot{Z}_{Mea}$-$\dot{Z}_{Cal}$)/ $\dot{Z}_{Cal}$*100%)	Average Error (%)
6	4	5741.0	5465.5	-4.8	
8	3	2625.4	2697.2	2.7	2.6
10	3	4102.2	4102.2	0	
12	3	5907.2	5743.4	-2.8	

(III), Cs^+ source, Si sample:

Ep (keV)	Knob Position	$\dot{Z}_{Cal}$ (Å/μA·min)	$\dot{Z}_{Mea}$ (Å/μA·min)	Error (($\dot{Z}_{Mea}$-$\dot{Z}_{Cal}$)/ $\dot{Z}_{Cal}$*100%)	Average Error (%)
6	4	2752.1	2205.7	-19.9	
8	3	1258.6	1295.0	2.9	
10	1	85.1	90.4	6.2	5.2
	2	544.8	549.5	0.9	
	3	1966.5	1966.5	0	
	4	7644.7	7904.6	3.4	
12	3	2831.8	2919.0	3.1	

(IV), Cs^+ source, GaAs sample:

Ep (keV)	Knob Position	$\dot{Z}_{Cal}$ (Å/μA·min)	$\dot{Z}_{Mea}$ (Å/μA·min)	Error (($\dot{Z}_{Mea}$-$\dot{Z}_{Cal}$)/ $\dot{Z}_{Cal}$*100%)	Average Error (%)
6	3	1843	1436	-21.9	
10	2	1418	1346	-5.1	10.3
	3	5118	5118	0	
13	2	2396	2050	-14.3	

a, $\dot{Z}_{Cal}$: calculated sputtering rate; $\dot{Z}_{Mea}$: measured sputtering rate.

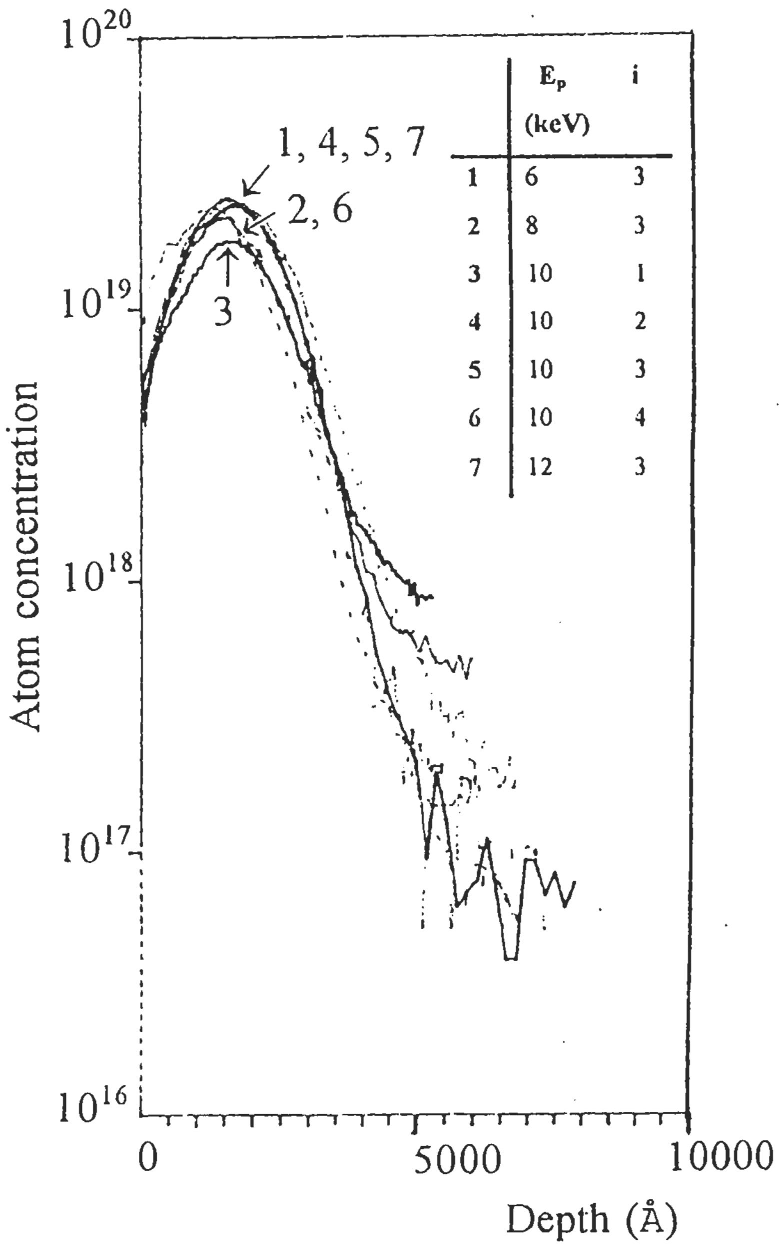

Figure 1. the depth profiles of ^{29}Si implanted GaAs sasmple (O_2^+ source)