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A Novel Probe Size Measurement Method for a Fine Electron Beam

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A novel electron beam (EB) spot size measurement method is proposed. In this method, EB spot size is obtained from the relationship between the width of the trenches in the reference sample and the intensity profile of backscattered electrons. Selective chemical etching of a GaAlAs/GaAs superlattice produces an ideal structure for the reference sample. Such superlattice is fabricated by metalorganic chemical vapor deposition and trench widths are verified by transmission electron microscopy. Using 0.6 μm deep and 8.5–65 nm wide trenches, nanometer-level EB spot sizes can be accurately measured.

KEYWORDS: electron beam diameter, measurement method, Gaussian distribution, reference sample, GaAlAs/GaAs superlattice

§1. Introduction

Fine focused electron beams are necessary in both electron beam (EB) lithography[1)] and EB metrology[2)] because the resolution limits in these technologies are heavily dependent on the spot sizes of the electron beams. Spot sizes in newer EB lithography and metrology systems have already reached the nanometer level. However, the accuracy of the conventional spot size measurement method using a knife edge is inadequate for nanometer-level EB spot size and profile measurement. The inaccuracy in the conventional spot size measurement method is mainly caused by the influence of transmitted electrons from the side wall of the knife edge, and the obtained spot size is not completely verified because of the lack of a standard reference. This paper proposes a novel spot size measurement method applicable to a fine electron beam. The method uses a specially fabricated reference sample having extremely narrow and deep trenches.

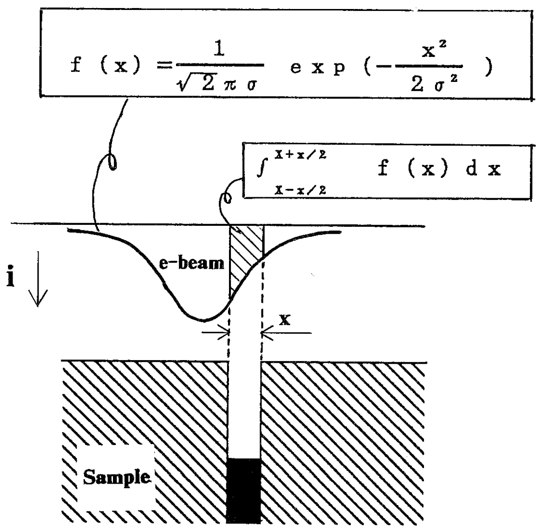

Fig. 1. Schematic of a Gaussian electron beam and a deep trench.

§2. Principle of Measurement Method

In this measurement method, EB spot size is obtained from the relationship between the widths of the trenches in the reference sample and the intensity profile of backscattered electrons.

First, it is assumed that the electron beam distribution is a Gaussian distribution. When the electron beam irradiates a trench having a known width x as shown in Fig. 1, no backscattered electrons can be reflected from the part of the EB spot projected into the trench. Then, the intensity profile of backscattered electrons, I, corresponds to the number of electrons backscattered from the outside of the EB spot, i.e., those projected onto the flat surface of the reference sample, as follows.

$$I(X, x, \sigma) = 1 - \int_{X-x/2}^{X+x/2} f(x)\,dx, \qquad (1)$$

$$f(x) = \frac{1}{\sqrt{2}\,\pi\sigma} \exp\left(-\frac{x^2}{2\sigma^2}\right), \qquad (2)$$

where, the total intensity of all backscattered electrons from the flat surface is normalized as unity, and X is the position of the EB spot, the origin of which is defined as the center of the trench. Figure 2 shows distributions of intensity I calculated for various values of X, x and σ. The minimum value of intensity I at $X=0$ approaches unity as the width of trench x is made narrower than EB spot size σ. Then, by preparing trenches as narrow as the EB spot size and measuring the width of trenches x and I_{min}, that is, I at $X=0$,

$$I_{min}(x, \sigma) = 1 - \int_{-x/2}^{x/2} \frac{1}{\sqrt{2}\,\pi\sigma} \exp\left(-\frac{x^2}{2\sigma^2}\right) dx, \qquad (3)$$

so, the EB spot size σ can be obtained accurately from eq. (3).

§3. Experimental

3.1 *Reference sample*

The key to accurate measurement is in creating a good reference sample. There are several requirements for a

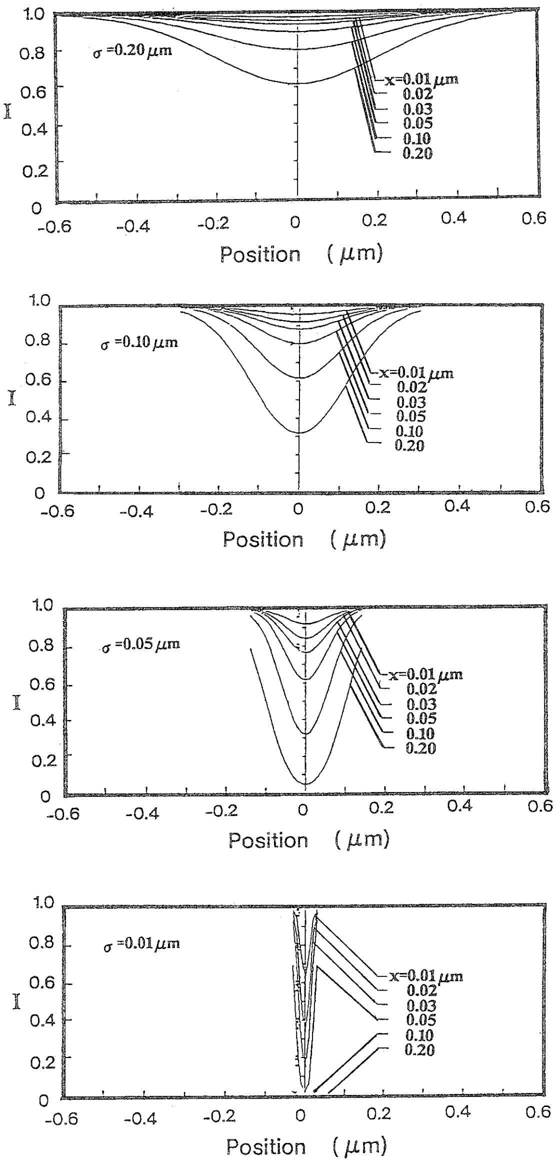

Fig. 2. Relationship between I, x, σ from calculation.

good reference sample. One is that the trenches of the reference sample be deep and their widths verified by accurate measuring. Another requirement is that the reference sample be stable and immune to charging under EB irradiation.

A GaAlAs/GaAs superlattice (Fig. 3) is adopted to implement very narrow and deep trenches. Such a superlattice can be fabricated by metalorganic chemical vapor deposition (MOCVD).

The thickness of each $Ga_{0.86}Al_{0.14}As$ layer is controlled during MOCVD to precisely one atomic layer and is measured by transmission electron microscopy (TEM) to an accuracy of 0.1 nm. Trenches 0.6 μm deep and 8.5–65 nm wide are obtained by selective chemical etching (H_2O_2:NH_4OH=250:1). As the etching rate ratio between $Ga_{0.86}Al_{0.14}As$ and $Ga_{0.5}Al_{0.5}As$ is extremely high and the compositional abruptness at the heterointerface is less than 0.5 nm, the trench wall is almost perpendicular and the difference between the thickness of each $Ga_{0.86}Al_{0.14}As$ layer and trench width x is less than 1 nm.

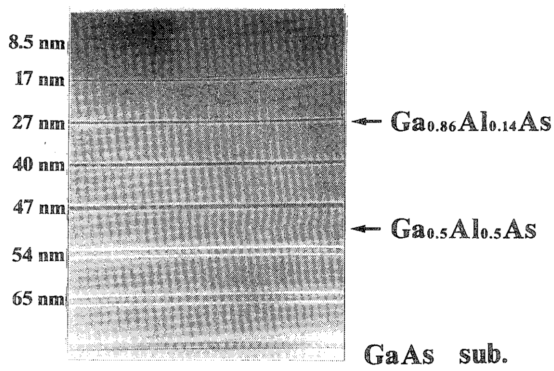

Fig. 3. SEM micrograph of GaAlAs/GaAs superlattice. Thickness of each $Ga_{0.86}Al_{0.14}As$ layer is verified by TEM measurement.

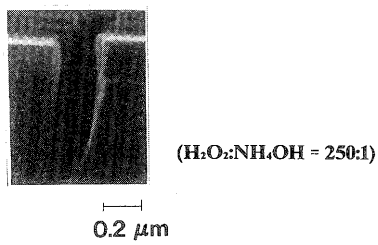

Fig. 4. SEM micrograph of cross sectional view of selective chemical etched trench.

The compositional abruptness at the heterointerface can be measured accurately by TEM using CAT (Composition Analysis by Thickness-fringe).[3] Figure 4 shows a scanning electron microscopy (SEM) micrograph of a selective chemical etched trench cross section. Such a trench gives a high-contrast signal, and absolutely verified calibration represents a suitable structure for the reference sample.

3.2 *EB spot size measurement*

An EB metrology system[4] is used for EB spot size measurement. The accelerating voltage is 0.5–2 kV and the beam current is 10 pA with a field emission gun. EB spot diameter, calculated from the electron optics parameters, is 10 nm. The images and intensity profiles from both backscattered and secondary electrons can be displayed.

§4. Results and Discussion

Figures 5 and 6 show the obtained intensity profiles and SEM images of backscattered and secondary electrons at 1.5 kV accelerating voltage. The signals from the secondary electrons are affected significantly by dispersion at the edge of a trench over 54 nm wide. This phenomenon does not depend on accelerating voltage. On the other hand, the signals from the backscattered electrons are stable and clear at every trench.

Therefore, the signals from the backscattered electrons are suitable for the proposed measuring method. In the waveform of backscattered electrons at 1.5 kV, all trenches can be identified. The waveform loses definition

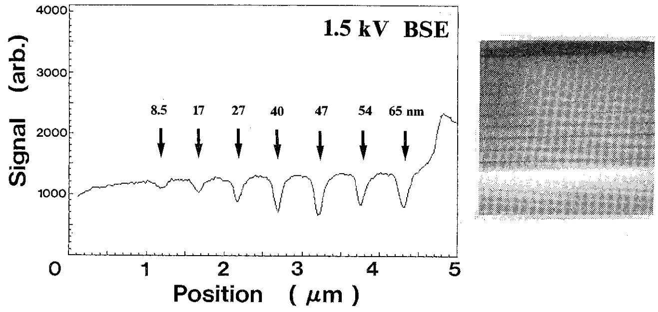

Fig. 5. Waveform of backscattered electrons (BSE) and SEM image at 1.5 kV.

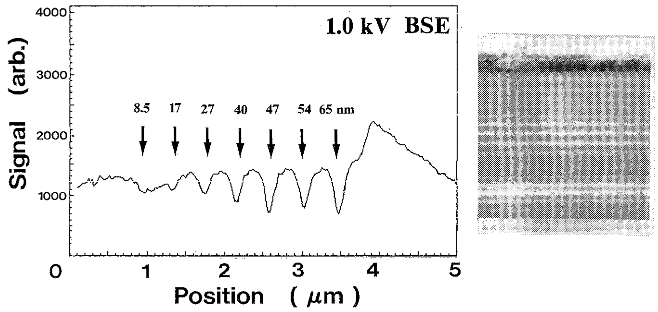

Fig. 7. Waveform of BSE and SEM image at 1.0 kV.

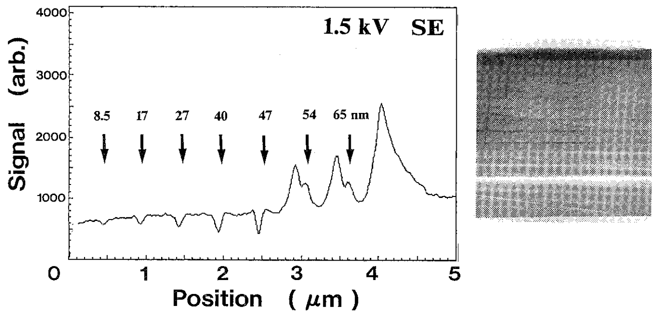

Fig. 6. Waveform of secondary electrons (SE) and SEM image at 1.5 kV.

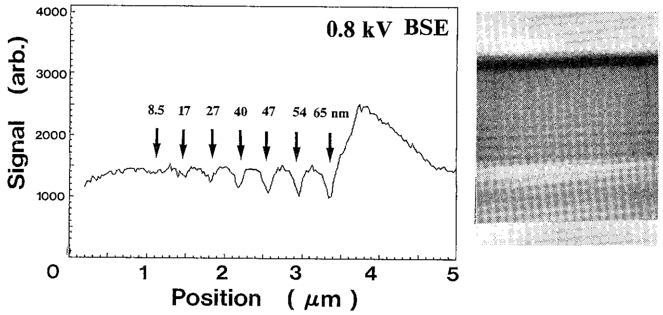

Fig. 8. Waveform of BSE and SEM image at 0.8 kV.

when the trenches become narrower than 27 nm. So, EB spot size σ is roughly estimated to be about 10 nm from the relationship between $I_{\min}$, x and σ as shown in Fig. 2. Furthermore, an accurate EB spot size is obtained by measuring the intensity of backscattered electrons $I_{\min}$ from each trench. For a 27 nm wide trench, the intensity of backscattered electrons I normalized by the intensity from the Faraday cup is 0.312. EB spot size σ then obtained is 13.4 nm by eq. (3) substituting I and x. In most cases, EB spot diameter d, defined as the diameter of a circle containing half the total beam current, is used as a physical parameter.[6] In the case of a Gaussian electron beam, EB spot diameter d is expressed by σ as follows.

$$d=1.67\sigma. \tag{4}$$

So, EB spot size d can be obtained from eq. (4) as 22.3 nm.

In the same way, EB spot size σ and diameter d at 1.5 kV acceleration are obtained from trenches 17 and 8.5 nm wide as shown in Table I. Then, the averaged EB spot diameter is 21 ± 3 nm. The differences between EB spot diameters obtained from each trench are very small, i.e., within ±3 nm. Therefore, the initial assumption that the electron beam distribution is a Gaussian distribution is supported by the experimental results. If more trenches of various widths are prepared, the precise distribution of an actual electron beam can be obtained.

EB spot sizes and diameter at 1.0 and 0.8 kV acceleration voltage are also measured. Figures 7 and 8 show the waveforms and SEM images of backscattered electrons at 1.0 and 0.8 kV acceleration voltage. The narrowest trench, 8.5 nm wide, cannot be detected in either case.

Table I. Results of EB spot size measurements.

E (kV)	x (nm)	$1-I_{\min}$	$I_{\min}$	σ (nm)	σ (ave.) (nm)	$d=1.67\sigma$ (nm)
1.5	27	0.688	0.312	13.35	13 ± 2	21 ± 3
	17	0.438	0.562	14.65		
	8.5	0.375	0.625	10.63		
1.0	40	0.750	0.250	17.39	16 ± 2	26 ± 3
	27	0.556	0.444	17.49		
	17	0.472	0.528	13.47		
0.8	40	0.692	0.308	19.63	18 ± 2	30 ± 3
	27	0.538	0.462	18.34		
	17	0.385	0.615	16.93		

Waveforms of the other trenches are less defined compared with the waveform at 1.5 kV (Fig. 5) as acceleration voltage is lower. As a result, it can be said that the EB spot size increases when the accelerating voltage decreases. EB spot size and diameter values obtained are listed in Table I. Averaged EB spot diameters at 1.0 and 0.8 kV are 26 ± 3 and 30 ± 3 nm, respectively.

Electron beam diameter d is given by the equation

$$d^2=d_s^2+d_c^2+d_d^2+d_o^2, \tag{5}$$

where,

$d_s=\frac{1}{2}C_s\alpha^3$; (spherical aberration),

C_s: spherical aberration coefficient of the lens
α: convergence semiangle

$d_c=\frac{\Delta E}{E}C_c\alpha$; (chromatic aberration),

E: electron energy
ΔE: energy spread of electrons
C_c: chromatic aberration coefficient of the lens

$d_d = \frac{1.22\sqrt{150/E}}{\alpha}$; (electron diffraction),

$d_o = M \cdot d_e$; (diameter with neither aberration nor diffraction).

M: reduction ratio of the electron optics
d_e: electron source diameter

With a field emission gun, ΔE becomes so small that the dependence of EB spot diameter d on electron energy E is due to electron diffraction only. Figure 9 shows the relationship between EB spot diameter and accelerating voltage. The solid line represents the case of electron diffraction limited diameter.

$$d \propto \sqrt{150/E} \quad (6)$$

where, E is electron energy. Experimental results agree with the relationship (6). It is then confirmed that EB spot diameters in this electron optics depends on electron diffraction.

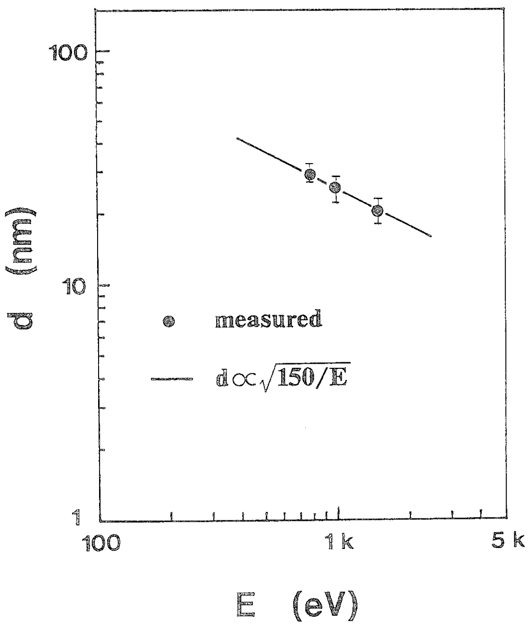

Fig. 9. Dependence of EB spot diameter d on electron energy E.

§5. Conclusion

A novel EB spot size measurement method using a reference sample with extremely narrow trenches has been proposed. Selective chemical etching of a GaAlAs/GaAs superlattice achieved an ideal structure for the reference sample. The precise trench widths were verified by TEM. The accuracy was on the order of less than 1 nm. Using trenches 0.6 μm deep and 8.5–65 nm wide, nanometer-level EB spot sizes could be measured accurately with this method. From the experimental results at 0.8–1.5 kV acceleration voltage, it was confirmed that EB spot diameters in the experiments depended on electron diffraction.

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