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HIGH ACCURACY AND AUTOMATIC MEASUREMENT OF THE PATTERN LINEWIDTH ON VERY LARGE SCALE INTEGRATED CIRCUITS

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Abstract

High accuracy measurement of pattern linewidth is particularly important in Very Large Scale Integrated Circuits(VLSI) manufacturing.

The measurement of pattern linewidth has been done by optical methods. However, the optical methods have several problems: as the measured value depends on slope angle at pattern edge, thickness and optical property of film and also substrate, there exists a large difference in size (0.3 μm) between the defined edge and the true edge in case of photoresist linewidth measurements. Especially,the optical methods have severe problems to measure bottom of pattern edge and are unsuitable to measure pattern linewidth in VLSI's manufacturing.

The secondary electron signal obtained by electron beam irradiation can be used to measure pattern linewidth with high accuracy. In order to avoid radiation damage and contamination during in-process measurement, low primary electron energy (1 keV) and low dosage of primary electrons ($1X10^{20}$electrons/cm^2) are used.

As secondary electron signal includes much random noise, signal averaging and smoothing methods for random noise reduction are utilized.

The automatic detection of bottom edge from secondary electron profile is achieved by detecting the increasing point of line profile which corresponds to the cross point of the average line and the slope line.

The linewidths obtained by this method agree with the linewidths calculated from the pattern pitch of cross section image obtained by scanning electron microscopy(SEM) within the error of 0.04μm.

KEYWORDS: Linewidth measurement,Scanning Electron Microscopy,Very large Scale Integrated Circuits, Charging up,Contamination,Radiation Damage,Signal Processing.

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Introduction

Electron beam technique has been playing an important role in the Very Large Scale Integrated Circuits(VLSI) development as a lithography tool. However, it also provides a novel method for accurate linewidth measurement as the most valuable technique in VLSI's manufacturing area.

Since the pattern linewidth becomes smaller and smaller, even a small change in pattern linewidth gives rise to remarkable change in the device characteristics. Therefore, it is extremely important to measure the pattern size with high accuracy and reliability. The commonly accepted optical measuring methods have many drawbacks due to scattering, diffraction and interference at pattern edge which always cause measurement errors.(4)

The present paper deals with the method in which the pattern linewidth is determined by utilizing topographic contrast of secondary electron signal obtained by low energy electron beam. Electron beam can ensure the high resolution image, and the secondary electron signal can sensitively detect surface topography and hence the pattern edge can be determined precisely.(1)(2) The low energy electron beam does not affect the electrical characteristics of integrated circuits(ICs) because of low charge-up and contamination during measurements.

The purpose of this paper is to discuss the problems and limitations of optical methods and then to extend the application of electron beam for measuring pattern linewidth in VLSI's manufacturing.

Problems and limitations of optical measuring methods

Figure 1 shows the typical methods of optical measurement for the pattern linewidth. Figure 1 (a) shows the threshold method in which a threshold level is set for the image signal obtained by using microscope and industrial television, and the pattern linewidth is defined by the length between two cross points at threshold level. Figure 1 (b) shows the laser scanning method that the scattering lights from pattern edge are detected by two detectors,A and B,and the pattern linewidth is defined by the moved distance measured by laser interferometer.

These methods utilize the change in brightness at pattern edge for linewidth determination. The signal is strongly affected by the slope of pattern edge. The object that we want to measure is the photoresist pattern linewidths. The photoresist thickness is usually 1 to 2 μm, and the pattern edge has a certain slope, and the photoresist and the substrate material are optically transparent or semi-transparent.

As the edge slope of photoresist patterns could take various fluctuations, the differences between the defined edge and the true edge would be affected by the scattering, diffraction and interference of light at the edges. They usually depend on the angle of edge slope, thickness of photoresist, optical nature of photoresist and substrate conditions, which leads to the conclusion that the optical measuring methods are unsuitable in the VLSI era.

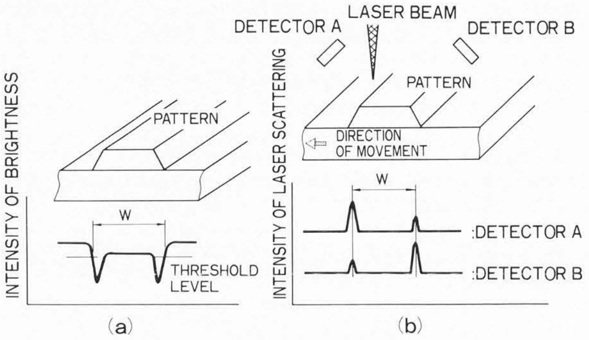


Fig.1 Typical methods of optical pattern linewidth measurement.

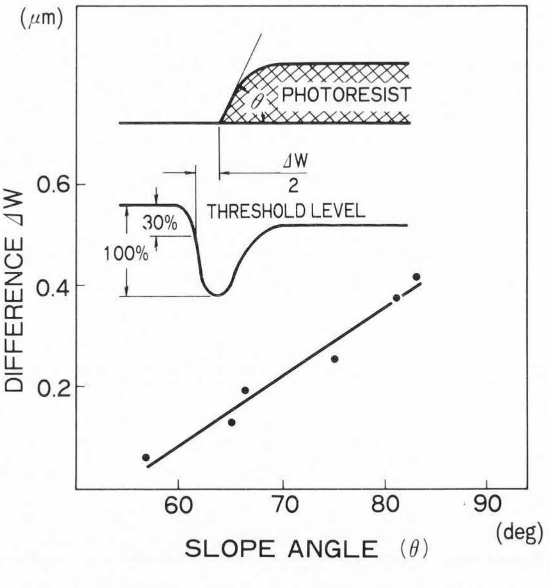


Fig.2 Difference in measured values in optical method and electron beam method. Dependence of the measured difference on slope angle at photoresist edge.

Comparison with optical and electron beam linewidth measurement

Figure 2 shows the relation between the slope angle of photoresist edge and the differences of optical and electron beam linewidth measurements. The linewidths in optical measuring method are determined by threshold level at 30 percent of the brightness signal. The linewidths in electron beam method are obtained by calculating from the pattern pitch of cross section image observed by SEM. The repeatability of the latter method is 0.015 μm. It is found that the linewidth in optical measuring method is larger than linewidth in electron beam method, and that the difference(ΔW) becomes larger with the increasing slope angle of photoresist (Θ).

The reason for this difference is presumably due to the optical phenomenon at the pattern edge i.e, scattering, diffraction and interference.

Furthermore, another problem of optical measuring methods is that high resolution image cannot be easily obtained, and that the linewidth below the wavelength of light cannot be measured. On the other hand, the secondary electron emission depends on the mass numbers of atoms constructing materials and also surface topography. As the mass numbers are almost the same in usual materials being used in silicon LSIs, their secondary electron emission efficiencies are about the same. Therefore, the contrast of secondary electron signal depends only on surface topography.

Consequently, the linewidth measurement by using topographic contrast of secondary electrons would be very suitable for VLSI in-process evaluation.

Application of electron beam for VLSI's manufacturing

The features of the electron beam method are as follows; (1) High spatial resolution image can be obtained. (2) The pattern edges can be detected precisely because the secondary electron signal depends on surface topography.

For the in-process measurements of the pattern linewidth, the following conditions must be satisfied: (1) It must be measured without any conductive coating on a chip to avoid electrostatic charging up. (2) It must be measured without leaving any irradiation effect on device characteristics. (3) It must be measured without surface contamination which might influence the subsequent process step.

Figure 3 shows the secondary electron image and its line profile signal when the electrostatic charging up occurs at relatively high primary electron energy(1.3 keV). In the figure, the remarkable contrast caused by the charging is observed and the secondary electron signal is distorted. Therefore, a precise measurement accompanied by the exact edge detection would not be expected.

According to our experiments, this problem can be avoided when the primary electron energy becomes less than 1 keV.

Furtheremore, the low primary electron

energy can solve the irradiation damage problems which might deteriorate semiconductor properties of devices during measurement.(3)

Figure 4 shows the results related to the contamination of chips by electron beam irradiation. Electron beam was scanned over the area shown in Fig.4(a). After the irradiation, the Poly-Si layer was etched by the plasma etching(chemical dry etching) as shown in 4(b). Figures 4(c) to (f) show the results of the etched Poly-Si layer. The irradiated dosages of primary electrons are (c); 3.21×10^{19} electrons/cm^2, (d); 9.63×10^{19} , (e); 1.61×10^{20} ,(f); 2.25×10^{20}, respectively. When the dosage of primary electrons exceeds 1×10^{20} electrons/cm^2,the irradiated area of Poly-Si is not etched. It is made clear through Auger spectroscopy that this phenomenon is due to the carbon contamination on the surface which will prevent the surface from etching. According to this experiment, the contamination by electron beam can be avoided when the dosage of primary electrons is less than 1×10^{20} electrons/cm^2.

As a result, it has become clear that the in-process linewidth measurement by electron beam can be made practically at low primary electron energy and low dosages.

Linewidth Measurement by electron beam

For the linewidth measurement in-process by electron beam, low primary electron energy and low dosage of primary electrons are necessary.

As a result, the decrease of signal to noise ratio of secondary electron signal cannot be avoided and the clear line profile cannot be obtained. Therefore, the improvement of signal to noise ratio by signal processing is necessary.

As the secondary electron signal includes a random noise, the noise reduction must be considered,which will be described below: (1) Fourier transform method (2) Smoothing method and (3) Signal averaging method.

In the Fourier transform, after the original signal is transformed and high frequency signal is removed, the signal is inversely Fourier transformed. This method has the demerit that the mathematical calculation is very time consuming, and also the equipment tends to be bigger.

In the smoothing method, the signal is calculated by the equation:

$$g(i) = \frac{\sum_{j=-\frac{n-1}{2}}^{\frac{n-1}{2}} k(j) f(i+j)}{\sum_{j=-\frac{n-1}{2}}^{\frac{n-1}{2}} k(j)} \qquad \begin{array}{r l} i: & \text{integer} \\ k(j): & \text{coefficient} \\ n: & 3,5,7,\ldots. \end{array}$$

where $f(i+j)$ is the intensity of secondary electron emission at each picture element before smoothing and $g(i)$ is that after smoothing.

In this method, when the noise component is large, it is difficult to separate the signal from the noise and the line profile cannot be easily reappeared, although the operating time is short.

The signal averaging method is most effective for reducing the random noise. But, as the electron beam must scan repeatedly, the total dosage of primary electrons increases. Therefore, in the allowable limit of total dosage of primary electrons, the effective improvement of signal to noise ratio cannot be obtained only by this processing.

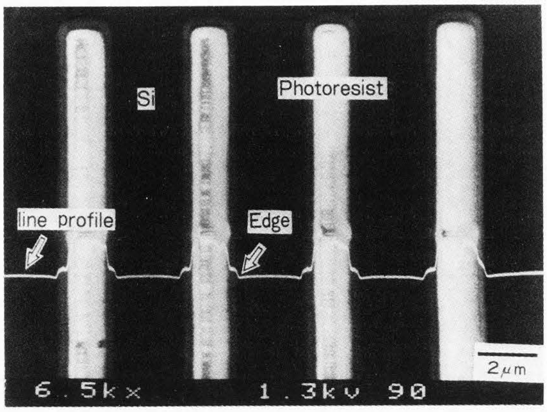
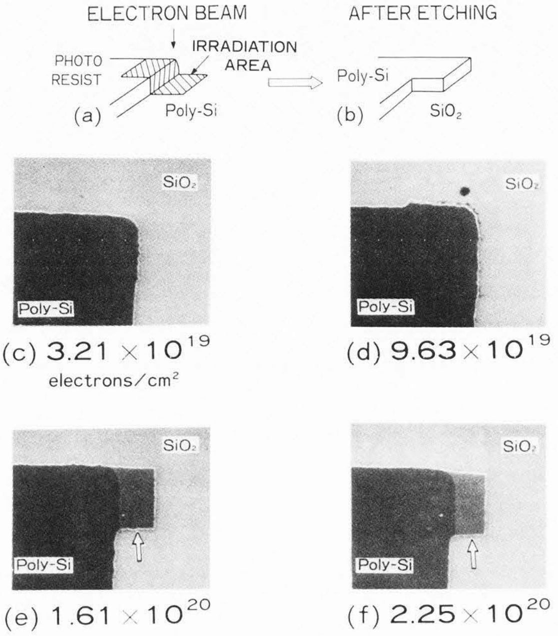


Fig.3 Secondary electron image and its line profile after charging up at high primary electron energy, 1.3 keV.



(c) 3.21×10^{19} electrons/cm^2

(d) 9.63×10^{19}

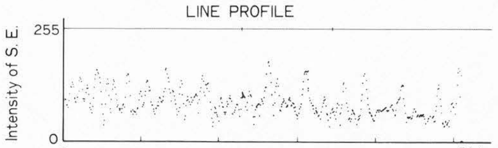
(e) 1.61×10^{20}

(f) 2.25×10^{20}

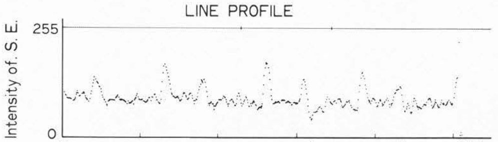
Fig.4 Contamination by electron beam irradiation. Dependence of the total dosage of primary electrons,(a) irradiation area,(b) after etching and removing photoresist, (c) 3.21×10^{19},(d) 9.63×10^{19},(e) 1.61×10^{20}, (f) 2.25×10^{20}. Arrows show the unetched Poly-Si (at 1 keV).

As a result the combination of smoothing and signal averaging would be suitable for signal processing.

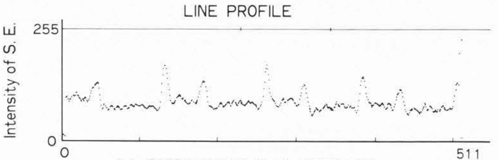
Figure 5 shows the experimental result by the optimum signal processing. The profile in Fig.5 is obtained by printing out after memorizing the analog to digital converted signal



(a) ORIGINAL SIGNAL



(b) SIGNAL AVERAGING(32 TIMES)



(c) SMOOTHING (9 ELEMENTS)

Fig.5 Optimum signal processing for secondary electron signal. (a) Original signal, (b) after averaging, (c) after smoothing

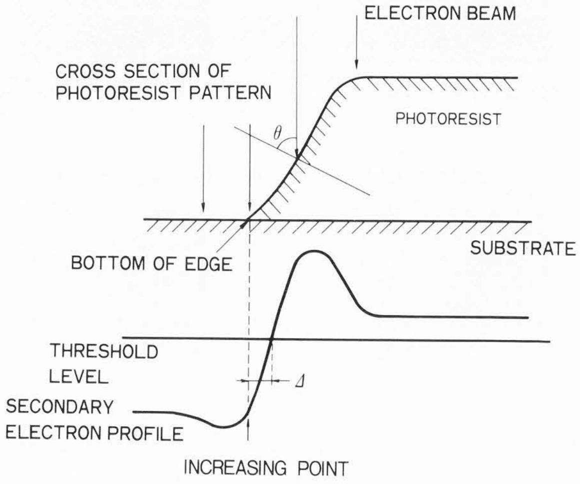


Fig.6 Model of secondary electron emission at pattern edge of photoresist.

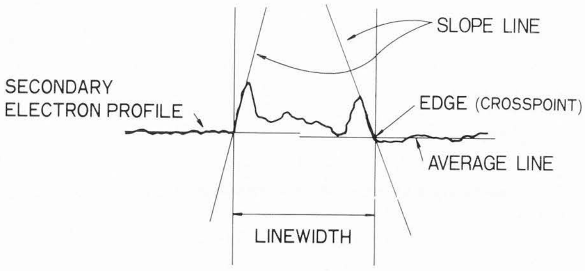


Fig.7 Model of edge detection method and linewidth measurement.

of secondary electrons.

Figure 5(a) shows the original line profile of secondary electron signal obtained at 1 keV and 15 pA. The measured sample is the photoresist on Si substrate. The original signal includes large random noises. After averaging 32 times as shown in Fig.5(b), it is found that the random noise is reduced effectively. Furthermore, the smoothing processing for the line profile in Fig.5(b) is shown in Fig.5(c). The reduction of random noise without changing the original line profile is obtained.

Figure 6 shows the schematic illustration of secondary electron profile at pattern edge. When the electron scans on the pattern, the intensity of secondary electron emission depends on the surface topography and the material. The signal starts increasing at the slope of pattern edge and decreasing at the top of pattern edge.

As the edge detection method from the line profile obtained by electron beam, the threshold method similar to the optical method is considered. The edge is decided by the crosspoint of threshold level and line profile as shown in Fig. 6. But, the edge that we want to measure is the bottom of pattern edge, because the bottom of photoresist pattern decides the etching width. In the case of the threshold method , as the crosspoint depends on the slope angle of photoresist(θ), the difference(Δ) appears leading to the conclusion that the threshold method is unsuitable for measuring the photoresist linewidth.

For detection of the bottom of edge, the manual measurement could be possible, but, the linewidth measurement in VLSI manufacturing is necessary to automatically detect the bottom of edge to avoid a certain error caused by human nature.

As shown in Fig.6, the automatic edge detection can be made possible by detecting the increasing point of line profile.

The principle of automatic edge detection for the line profile obtained by electron beam that we have developed is shown in Fig.7.

For detection of the increasing point of line profile, the line profile is replaced by two lines at pattern edge. One is the average line of secondary electron profile at the substrate. Another is the slope line of secondary electron profile at edge slope. The cross point of two lines is defined as the bottom of pattern edge. The automatic detection of edge bottom can be made by calculating the cross point of the average line and the slope line. Then the linewidth is measured automatically.

Figure 8 shows the block diagram of the automatic linewidth measurement system.

The secondary electron signal from SEM is converted from analog to digital signal and memorized in frame memory (512X512X8). For reducing random noise, the signal averaging of 32 times is operated by synchronizing with the secondary electron signal from SEM. Furthermore, the smoothing is made for the profile obtained by the signal averaging. The automatic edge detection and linewidth measurement are established by calculating the cross point of the

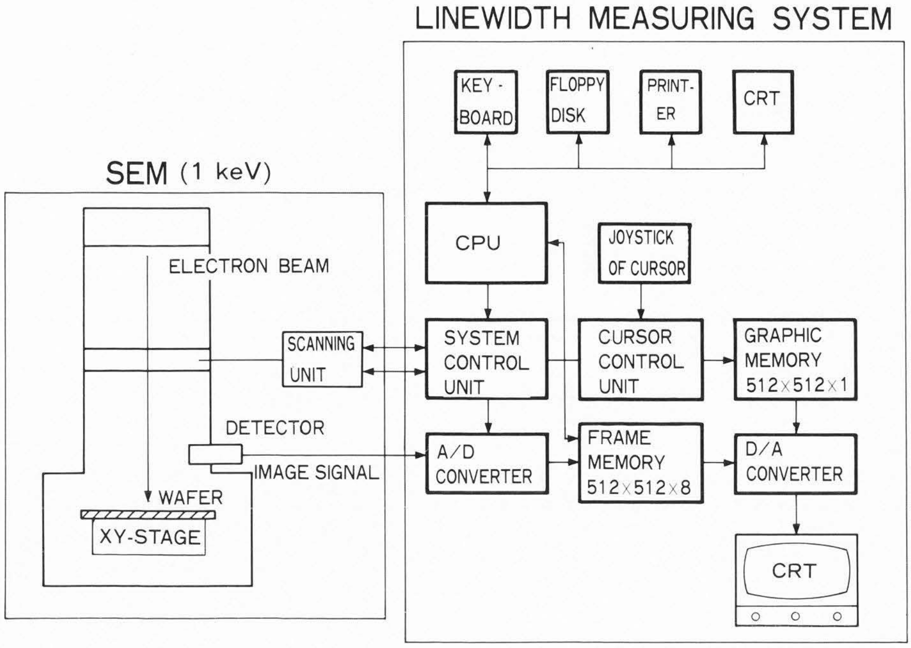


Fig.8 Block diagram of the developed electron beam linewidth measurement system.

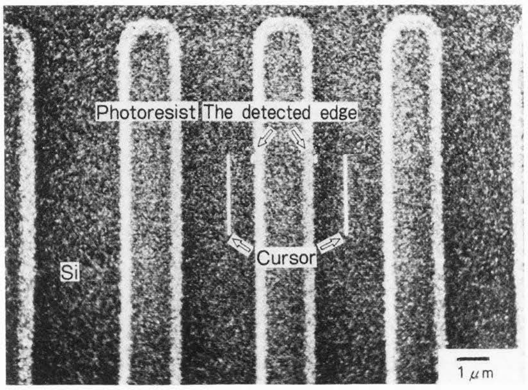


Fig.9 CRT display of measurements result. Dots show the obtained pattern edges by automatic edge detection.

average line and the slope line for the obtained profile. The result of calculation is displayed on the cathode ray tube(CRT) as shown in Fig. 9. The two cursors appoint the place to be measured. The obtained cross points are displayed as dots on the CRT. The linewidths obtained by this method agree with the linewidths with the error of 0.04μm which are calculated from the pattern pitch of cross section image obtained by SEM.

As a result, it is found that the linewidth measurement by electron beam is effective in VLSI manufacturing.

Summary

The high accuracy measuring methods of photoresist pattern linewidth have been described.

It is found that the optical measuring methods are unsuitable in VLSI manufacturing, because they give rise to the differences of 0.3μm between the defined edge and the true edge.

The application of electron beam has been investigated for the in-process linewidth measurement. It is found that the low primary electron energy (1 keV) and low dosage primary electrons ($1X10^{20}$ electrons/cm^2) are necessary to avoid electrostatic charging up, radiation damage and contamination of surface layer by electron beam.

It is suggested that the signal processing employing both averaging and smoothing is important to effectively reduce random noise from secondary electron signal,and to obtain accurate topographic information.

The automatic edge detection and measurement of pattern linewidth from secondary electron profile have been proposed in which the automatic edge bottom detection can be made by calculating the cross point of the average line and the slope line from the line profile.

By using this measuring method, the accuracy of 0.04μm was obtained.

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Discussion with Reviewers

H. Niedrig: Within the Introduction you state that since the mass numbers of materials in silicon LSIs are almost the same, their secondary electron emission efficiencies are approximately equal. Is that true? As far as I know the SE coefficient vary rather strong between neighboured elements(see, e.g., H. Seiler, J. Appl. Phys. 54 (11) 1983, R1-R8).
Authors: The paper of H. Seiler describes that there exists no simple relation between SE yield and the atomic number Z of the surface atoms. But, when the atomic number Z differs, SE yield changes. By our experiments, the contrast of SEM image for semiconductor composition materials is observed as almost same at 1.0 keV.

K. Ura: What are the accelerating voltage and the size in Fig.4?
Authors: We used the accelerating voltage of 1.0 kV and the beam diameter of about 110 Å.

K. Ura: How are the wavelength, spot diameter and aperture angle of the laser used in Fig.2?
Authors: We used the commercial equipment, e.g. Nikon LAMPAS. (See its catalogue for details.)

V.N.E. Robinson: Would I be correct in assuming that your beam diameter d_0 was approximately 20nm, and that your accuracy of ±40nm was $2d_0$?
Authors: No, your assumption would not be correct. We used the beam diameter of about 11nm. But, since the picture element of frame memory was 20nm at 10,000 magnifications, our accuracy became 40nm.

V.N.E. Robinson: Do you carry out your smoothing /averaging along a line, or by multiple scanning?
Authors: We carry out averaging by multiple scanning(32 times) and smoothing along a line obtained by averaging.

J.D. Reimer: What radiation damage have you experienced and in which types of VLSI ICs?
Authors: We have experienced the changes in MOS electrical parameters such as threshold voltage and drain leakage current as a result of irradiation (see text reference (3)).

J.D. Reimer: In your experiments, what was the highest primary electron energy at which you could safely make linewidth measurement without encountering radiation damage to your IC?
Authors: We didn't investigate it in detail. But, we think that it is 1.0keV, because, in measuring photoresist pattern, the electrostatic charging occurs at 1.3keV and we cannot measure the linewidth with high accuracy.

H. Niedrig: Recently W. Stickel and G. O. Langner published a new definition of edge contrast for comparative lithography tool characterization (J. Vac. Sci. Technol. B 1 (4), 1983, 1007-1010). Does this fit with your method of edge detection shown in fig. 7?
Authors: The paper of W.Stickel et al describes about the definition for characterizing the resolution capability of the lithography tool, not about the definition of pattern edge in line width measurement.
Therefore, We think their definition is not related to our definition.