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Improvement of Resolution for Electron-Acoustic Microscopy

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Abstract

The resolution (r) of our electron-acoustic microscopy (EAM) has been $1.2 \mu m \leq r \leq 2.4 \mu m$, when operated with electron beam chopping frequency (f) of 1 MHz, duty ratio of 50% and acceleration voltage (HV) of 30 kV. This level of r is insufficient for observation of metal-oxide-semiconductor (MOS) LSI. This problem was partly solved by improvement of a driving power unit for chopping an electron beam so that the harmonic components on the square wave of f which flow in the chopping coil could be drastically suppressed. The r obtained was estimated to be $r \leq 0.8 \mu m$ at $f=1$ MHz, duty ratio=50% and HV=19 kV. If f can be further increased by this method, r would further improve, and application of EAM to nondestructive observation at the selected area, i.e., the fixed area, of MOS LSI would be come possible.

Keywords: Electron-acoustic microscopy, Ultrasonic, Nondestructive observation, Scanning electron microscopy, Device analysis

1. Introduction

Electron-acoustic microscopy (EAM) was proposed as a method of nondestructive internal observation using chopped electron beam.¹ ² By irradiation of a chopped electron beam, the specimen is repeatedly heated and cooled in response to irradiation and nonirradiation, and the power of the beam is converted to a thermal wave³ and propagates within the specimen. And then the thermal wave is converted to an acoustic signal during propagation in the specimen. The acoustic signal reaches the reverse side of the specimen by propagation of the specimen. This electron acoustic (EA) signal, the acoustic signal generated by irradiation of a chopped electron beam, is picked up by a piezoelectric detector (PZT device) attached to the back of the specimen. The signal is amplified by a lock-in amplifier (LIA) in
synchronism with the chopping frequency (f) of the irradiated electron beam. The output signal is displayed as a video signal on CRT in synchronism with the scanning of electron beam by utilization of the mechanism of scanning electron microscopy (SEM), to obtain an electron acoustic image (EAI).\textsuperscript{3–14)}

At first, selecting the site of observation from SEM mode images and then switching to an EAM mode, nondestructive observation of the internal structure was carried out at the selected area, i.e., the fixed area.\textsuperscript{3–14)}

Recently, the scale of integration has further advanced for metal–oxide–semiconductor (MOS) LSI, and the manufacture by a 0.25 \( \mu \)m rule has been commenced. A method of selective nondestructive observation at any site desired is necessary for failure analysis of such devices. EAM is a system which allows nondestructive internal observation of the selected area at first from SEM mode images.\textsuperscript{3–14)} EAM is, therefore, considered best suited for this purpose.

MOS devices are generally known to be highly susceptible to damage by irradiation of an electron beam. Therefore, problems that need to be solved for EAM observation of these devices are (a) reduction of irradiation-induced damage to MOS devices and (b) improvement of resolution (r).

By improvement of a signal detector and an amplifier for our EAM system, we succeeded to improve S/N and to reduce the absorption current (Is) to approximately \( 8 \times 10^{-10} \) A\textsuperscript{14)} (about 1/10 of the previous level\textsuperscript{2–13}). With this improvement, electron beam-induced damage to MOS LSI specimens (problem (a)) could be diminished. At the same time, improvement of r (problem (b)) could also be achieved to some extent but not sufficient.

We attempted to improve the r (problem (b)) of our EAM by improvement of the power source of the electron beam chopping unit, and carried out nondestructive internal observation of MOS LSI as a specimen.

\section*{2. Experimental Method}

The following items (A) and (B) are the major factors which determine the r of EAM as under:

(A) : When the disatance of the irradiated electron beam losses its energy in the specimen, the electron range (Re) is given by Castaing's equation:\textsuperscript{15)} as under.\[Re=0.033(HV^{1.7}-V_k^{1.7})A/\rho Z\] (1)

Where A: atomic weight, HV: acceleration voltage, \( V_k \): threshold voltage of K-line, Z: atomic number and \( \rho \): density.

From eq. (1) it is necessary for improvement of Re to decrease HV which was narrow down the volume of EA signal generation by the beam. Therefore, decrease of HV was related improvement of the r.

We have carried out EAM observation of a variety of bipolar transistor chips. We
have chosen HV as a variable while using f (f=1 MHz and duty ratio=50 %) as a constant, because our main interest has lain in determining the observable depth (tx)\textsuperscript{13,14} while maintaining r on a constant level, and have found that it was possible to increase tx by increasing HV and Re\textsuperscript{3-14}.

The active region in MOS LSI extends to a depth of only a few micron-maters from the surface. High HV is not required for observation at this depth. Low HV contributes to the decrease in Re and improvement of r.

(B): The thermal diffusion length (dt\textsuperscript{1,2}) of heat generated by irradiation of an electron beam is given by

\[ dt = \left( \frac{4 \pi \kappa}{\rho c f} \right)^{1/2} \]  

Where f: chopping frequency of a beam, \( \kappa \): thermal conductivity and c: specific heat.

When a target material is selected, \( \kappa, \rho \) and c are fixed by eq. (2), and only f remains as a variable. With our EAM system, the increase in f above 1 MHz was practically impossible, because the reference frequency of LIA was fixed (1 MHz) and the upper limit of frequency for the chopping unit (i.e., old unit) was 1 MHz. As the second best solution, we decided to modify the driving source of our chopping unit (i.e., new unit) so that the intermittent electron beam could be controlled by complete alternation of “on and off” intervals with waveform of the f.

In our EAM system, a square wave current of the f is fed into the coil so that the electron beam is chopped by deflection with a magnetic field generated. Application of a square wave current to the coil generates numerous harmonics in the waveform, and de to the irregularity of the driving waveform of f, the chopped electron beam is not the strict alternation of “on and off” intervals with the f, because the beam is dependent on the driving waveform. Modification of the chopping unit could not be accomplished by simple mechanical adjustment of our system. Therefore, we fabricated a new square wave power source which drove the coil (new unit). The results obtained were evaluated by comparison of the EAI's obtained with the old unit and those with the new unit. The operating condition of the EAM was f of 1 MHz, duty ratio of 50 % and HV was a variable. Substrate electrode of the chip was grounded.

3. Experimental Results

Figure 1(a) shows a backscattered electron image (BEI) and Fig. 1(b) shows the arrangement of surface electrodes. Comparison of EAI's using the old unit and the new unit are shown in Figs. 1(c) and 1(d) under the same operational condition, respectively. The latter (Fig. 1(d)) is clearly sharp image.

Figure 2 show EAI's of almost the similar area (see Fig. 1(b)) obtained by EAM observation with the various operating condition of EAM, and then EAI's were compared the old unit between the new unit. The upper column in Fig. 2 show EAI's using the old unit and the observation area was the same of Figs. 1(a), 1(b) and 1(c). The down
Figure 1. Surface image and arrangements of specimen near the observation area and comparison of EAI using the old unit and new unit with the same operational condition.
(a): BEI (SEM mode), (b): arrangement of surface electrodes, (c): EAI, HV=20 kV, old unit and (d): EAI, HV=20 kV, new unit.

column show EAI using the new unit and the area rotated from Fig. 1(b). The down column is higher magnification EAI than the case of old unit.

Figure 2(a) shows an EAI obtained with the old unit and Fig. 2(d) that obtained with the new unit when HV=19 kV. ① and ② (see Fig. 1(b)) are the repetition of square patterns of 0.8×0.8 μm² in size (see Figs. 1(b) and 3(b)). When HV=17 kV, compared between Figs. 2(b) and 2(e), the latter, the image from the new unit, gives a sharper image.

Figures 2(c) and 2(f) show EAI obtained with HV=15 kV using the old unit and the new unit, respectively. In Fig. 2(c) (the old unit), the image has no detail. On the other hand, the image in Fig. 2(f), it is that the squares have sharper right angles and that magnification is higher than the case of Fig. 2(c).

With the EAM system using the old chopping unit operated with HV below 15 kV, the EAI was poor and provided almost no information from the fixed area. Figure 2 (g) shows an EAI obtained with HV=14 kV using the new unit. The image in Fig. 2(g) was more clearly than the case of HV=15 kV using the old unit (Fig. 2(c)).

Figure 3(a) show EAI obtained with HV of 19 kV using the new unit and Fig. 3(b) is the cross sectional view near ① and ② (see Fig. 1(b)). The image of the squares have clearly sharper right angles. This demonstrates the improvement of resolution of the new unit, which is estimated to be r ≤ 0.8 μm.

This confirms the effectiveness of the improvement of the new chopping unit.

4. Discussion

Harmonic components of the square wave flowing in the electron beam chopping coil could be drastically suppressed by improving the power source of the chopping unit. The r after improvement was estimated to be r ≤ 0.8 μm and could thus be improved from the previous level of 1.2 μm ≤ r ≤ 2.4 μm.6) In this study, the r is considered only a plane and is not contained a depth direction.
Figure 2. EAls under various conditions from the selected area

The upper column ((a), (b) and (c)) is images using the old unit and the down column ((d), (e), (f) and (g)) is images the new unit under various HV conditions.
(a): HV=19 kV with the old unit, (b): HV=17 kV (old unit)
(c): HV=15 kV (old unit), (d): HV=19 kV with the new unit
(e): HV=17 kV (new unit), (f): HV=15 kV (new unit) and
(g): HV=14 kV (new unit).

The symbols are the same of those in Fig. 1. Magnification is higher the images of the new unit than the old unit.

Figure 3. EAI using the new unit
(a): EAI, HV=19 kV, f=1 MHz and duty ratio=50 %.
(b): cross sectional view of the squares.
①: squares for via holes, 0.8×0.8 μm² in size, and ②: squares for contact holes, 0.8×0.8 μm² in size. S: soft solder and G: glue bond.

The symbols are the same of those in Figs. 1 and 2.

But r of depth direction may be under 0.8 μm because ① in Fig. 3 is clearly separated that SiO₂ layer embedded second Al layer (0.8 μm thick, see Fig. 1(c)) is clearly detected. r of a depth direction should be reported otherwhere.
Equation (2) shows that \( dt \) decreases in proportion to \( (1/f)^{1/2} \), since \( dt \) is a determinant of \( r \). Therefore, the relation from eq. (2) among \( dt \), \( r \) and \( f \) is
\[
r \propto dt \propto (1/f)^{1/2}
\]
This relation is re-written as
\[
r = k (1/f)^{1/2}
\]
Where \( k \) is a constant.

Since \( f = 1 \) MHz and \( r = 0.8 \) \( \mu \)m (in this study), \( r = 0.25 \) \( \mu \)m and 0.20 \( \mu \)m can be achieved with \( f = 10.24 \) MHz and \( f = 16 \) MHz by simple calculation from eq. (4), respectively. For example, in the case of scanning acoustic microscopy using irradiated acoustic signal, \( r \) of 200 Å has been obtained with 8 GHz as reported by Hadimioglu and Foster.\(^{16}\) Therefore, if \( f \) can be further increased by this technique, it will be easy to further improve \( r \) and this makes application of EAM to nondestructive internal observation of MOS LSI at a selected area, i.e., a fixed area, possible.

5. Conclusion

The resolution (\( r \)) of EAM could be improved by drastically suppressing the harmonic components from the driving square wave of the \( f \) flowing in the electron beam chopping coil.

By this improvement, the \( r \) was estimated to be \( r \leq 0.8 \) \( \mu \)m with \( f = 1 \) MHz, duty ratio=50 \% and \( HV = 19 \) kV, and could thus be improved from the previous level of 1.2 \( \mu \)m \( \leq r \leq 2.4 \) \( \mu \)m.

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