enclosed source than in a conventional source because the pumping speed of source apertures is greatly reduced. Consequently the order of magnitude difference used in our discussion is very conservative. The values chosen are not atypical and the conclusion that the two methods provide comparable absolute sensitivities is valid.

* Presented in part at the Annual Conference on Mass Spectroscopy and Allied Topics, arranged by ASTM Committee E-14 in Dallas, Texas, 1 May 1969.
† Alfred P. Sloan fellow.
‡ This investigation was supported in part by a Public Health Service Research Career Development Award, No. 1 K04 GM42390-01, from the National Institutes of General Medical Sciences.

THE REVIEW OF SCIENTIFIC INSTRUMENTS

VOLUME 42, NUMBER 2 FEBRUARY 1971

Stroboscopic Scanning Electron Microscopy at Gigahertz Frequencies*

G. Y. Robinson†

Department of Electrical Engineering and Computer Science and Electronics Research Laboratory,
University of California, Berkeley, California 94720

(Received 26 June 1970)

Techniques for achieving a microwave time resolving capability in a scanning electron microscope using the stroboscopic mode of operation are presented. By pulsing the primary electron beam with traveling wave electrostatic deflection plates, an over-all system bandwidth in excess of 2 GHz is achieved. A method to detect fast primary electron beam pulses is also reported. Time varying surface potential measurements using secondary electron emission are given to demonstrate the microwave frequency response.

INTRODUCTION

Recenalty interest has developed in applying the scanning electron microscope (SEM) to study time dependent phenomena, particularly the surface potential distributions on solid state devices.1–4 There are several modes of operation possible when employing time resolved SEM with the stroboscopic mode being the most direct technique to achieve a large bandwidth when viewing repetitive phenomena.4 Here we present the experimental techniques which provide gigahertz frequency response in the stroboscopic mode of operation. To demonstrate the time resolving capability of stroboscopic SEM, secondary electron emission is used to measure the time varying surface potential of a planar semiconductor device at frequencies up to 2 GHz.

In the stroboscopic mode of time resolved scanning microscopy, the primary electron beam is turned on and off in synchronism with the repetitive phenomena under examination. The duration of the resulting primary beam pulses must be comparable with or smaller than the shortest significant time of the phenomena under study; otherwise, the time varying portion of the signal produced by the primary beam will be lost. Whether the information produced by the beam is secondary electron emission, beam induced currents, etc., the main factor determining the over-all frequency response of the stroboscopic mode is the width and shape of the primary beam pulse at the surface of the sample. Thus, when designing a stroboscopic microscope, the production of very short duration primary electron beam pulses is of major concern. In addition, the electron beam pulses should be created in a reproducible form and in a manner that permits accurate synchronization with the experiment in progress. Finally, the equipment necessary to implement the stroboscopic mode should create a minimum amount of interference with the conventional operation of the SEM. The following sections describe such a system with an over-all frequency response in excess of 2 GHz.
I. PRODUCTION OF PRIMARY BEAM PULSE

To achieve a microwave bandwidth for the stroboscopic system, the primary beam must be of subnanosecond duration. Such short duration pulses were created while avoiding major modification of our present instrument by sweeping the primary beam across a small aperture with electrostatic deflection plates (see right half of Fig. 1). To achieve rapid deflection of the beam at low voltages, the traveling wave deflection plates from the vertical deflection assembly of a Tektronix 519 oscilloscope were used. The plates were mounted in a removable jig which could be easily placed in alignment on the beam axis directly under the electron gun of the microscope. The deflection unit itself consisted of two deflection plates: one which was segmented and tapped to a delay line to form the traveling wave structure and the other which provided a ground plane for rapidly varying signals and which could also be floated at an independent dc voltage. Thus, a high frequency signal was applied to input A of Fig. 1 to produce a rapidly pulsed primary electron beam while a dc signal was applied to input B to hold the beam in either a normally-off or normally-on position. Input A had a characteristic impedance of 125 Ω while the external equipment had an impedance of 50 Ω; hence, a passive impedance matching circuit was mounted directly on the deflection unit. The input signal was then fed into port C through a microwave high vacuum feedthrough connector and applied directly to the matching circuit.

The performance of this deflection scheme was very satisfactory. The Tektronix 519 deflection unit was originally designed to operate with a 4 kV electron beam. However, to maintain sufficient electron beam current in the SEM, the beam was operated at voltages from 8 to 12 kV. The lack of synchronization between the phase velocity of the traveling wave structure and the electron beam velocity should appreciably degrade the performance of the deflection structure. For a 10 kV beam, we have measured approximately 50% decrease in deflection sensitivity from that specified by Tektronix. However, even with this loss of sensitivity adequate performance was obtained. Using an aperture of 1.5 mm in diameter mounted 8.0 cm from the deflection unit, 3.0 V applied to input C was sufficient for 100% modulation of the electron beam. This sensitivity could be maintained to sweep rates well over 10^6 V/sec.

The primary electron beam has been chopped by two different methods. When it was desired to produce a series of closely spaced, short duration primary beam pulses, a sine wave of several volts amplitude was applied directly to input C while input B was grounded. The primary beam was then swept back and forth across the aperture producing electron beam pulses at a repetition rate twice that of the frequency of the applied sine wave.

Using the deflection unit described above, we have produced pulses of less than 0.3 nsec duration at a repetition rate of 900 MHz. Using large amplitude sine waves, one should be able to produce electron beam pulses less than 100 psec in duration.

When it was desired to produce a single electron beam pulse synchronized with external equipment, a different method was employed. A dc voltage was applied to input B (Fig. 1) to hold the beam in a normally off position and a short duration voltage pulse of polarity and peak amplitude approximately equal to that of the dc voltage was applied to input C. The primary beam passed through the aperture only while the deflection pulse was on. By using external equipment to trigger the deflection pulse, this method placed a single primary beam pulse at the surface of the specimen in synchronism with the phenomenon under investigation. This was particularly advantageous when examining nonsinusoidal surface potentials.

We have used the system of Fig. 1 to produce triggered primary electron beam pulses of less than 200 psec duration. Commercial pulse generators are available with several tens of volts output, but not with subnanosecond pulse widths. By modifying a Lumatron model 2305 pretriggerable pulse generator for a minimum pulse width and maximum pulse amplitude, a pulse of approximately 40 V amplitude and 1.5 nsec width was produced [Fig. 1(a)]. This voltage pulse was reduced in width by passing it through a pulse shaping circuit which employed step recovery diodes. The resulting 35 V, 0.5 nsec pulse was applied to input C of the deflection unit while approximately +33 V dc was applied to input B. Since only 3 V were needed for the beam current to come to its peak
value, the beam could turn on only between approximately 32 and 35 V, i.e., only at the peak of the deflection pulse. Hence the width of the resulting primary electron beam pulse was expected to be even less than the width of the applied deflection voltage at input C. Figure 2 shows a typical electron beam pulse detected at the surface of a specimen. The measured width of the pulse at half its maximum value is seen to be 200 psec and, as shown in the next section, the actual beam pulse width was estimated to be 150 psec.

II. DETECTION OF PRIMARY BEAM PULSE

Before employing the above system for stroboscopic experiments, it was necessary to determine accurately the shape and width of the primary electron beam pulse at the surface of the specimen. The subnanosecond low energy electron beam pulses were detected by placing a solid state photodiode biased in the reverse direction directly under the primary beam and measuring the electron beam induced current produced by the diode. Two types of photodiodes have been used: the p–n junction avalanche diode and the Schottky barrier diode. Since the response of all the diodes tested varied with frequency in the microwave region, the effect of the diode on the measured response had to be first calculated and then subtracted out before an accurate estimate of the width of the primary beam pulse could be obtained. The frequency response of each diode was found by the following procedure: (1) measurement of the impedance of the diode and its holder at 100 kHz, 1 GHz, and 4 GHz and determination of an equivalent circuit (Fig. 3) which was consistent with the impedance measurements, (2) calculation of the upper half-power frequency as determined by the equivalent circuit, (3) calculation of the half-power frequency as determined by the transit time of induced mobile carriers through the space charge region of the diode, and (4) calculation of the over-all half-power frequency and the minimum pulse width at the output for an impulse electron beam at the input.

The calculated responses for three different diodes are shown in Table I along with the measured values of the widths of single pulses produced by the deflection scheme of Fig. 1. Agreement between the expected and observed behavior is seen to decrease as the calculated frequency response increases. This disagreement shows that the primary electron beam pulse was not an impulse function but rather a pulse of finite width. Tests on eight photodiodes indicated that the primary electron beam pulse was approximately 150 psec wide. This value of the minimum pulse width correlated with an independent measurement using a sinusoidal voltage applied to the deflection unit and to the calculated value of the minimum pulse width obtainable using the entire system shown in Fig. 1. A typical output waveform from a photodiode as observed on a 28 psec sampling oscilloscope is shown in Fig. 2. This particular diode is a gold–silicon (n type) Schottky barrier diode at 10 V reverse bias.

From Table I, the Schottky barrier diode had the highest frequency response and thus gave the most faithful representation of the actual primary electron beam pulse. However, the internal gain of the avalanche diodes (denoted as $M$ in Table I) often made them more practical as electron beam detectors than Schottky barrier diodes.

<table>
<thead>
<tr>
<th>Photodiode</th>
<th>Active area (cm$^2$)</th>
<th>Multiplication factor $M$</th>
<th>Measured circuit values (see Fig. 3)</th>
<th>Calculated upper half-power frequency (GHz) as determined by:</th>
<th>Calculated over-all response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guard ring n$^+$–p Si avalanche</td>
<td>0.14</td>
<td>10–15</td>
<td>3.0 16 3.2</td>
<td>Circuit Depletion layer transit</td>
<td>Upper-half power frequency (GHz) Pulse width (psec) Measured pulse width (psec)</td>
</tr>
<tr>
<td>Guard ring n$^+$–p Ge avalanche</td>
<td>0.44</td>
<td>10–20</td>
<td>2.0 40 1.3</td>
<td>1.0 3.4</td>
<td>0.98 360 370</td>
</tr>
<tr>
<td>Au–n Si Schottky barrier</td>
<td>1.01</td>
<td>1</td>
<td>3.0 20 0.36</td>
<td>1.8 7.5</td>
<td>1.7 210 260</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11 3.5</td>
<td>3.4 100 180</td>
</tr>
</tbody>
</table>
Because the electron beam currents normally used in the SEM were low and because the wide bandwidth display oscilloscope had low sensitivity, the avalanche photodiodes usually achieved a better signal-to-noise ratio than the Schottky barrier diodes under the same operating conditions but at a sacrifice in detector frequency response.

III. PERFORMANCE

We noted earlier that the over-all bandwidth of the stroboscopic mode is determined only by the shape and width of the primary beam pulse when it arrives at the surface of the specimen. It is not difficult to show that the frequency response of the stroboscopic mode is essentially the Fourier transform of the primary electron beam current $I_B(t)$ at the specimen surface. If $I_B(t)$ is assumed to be triangular in shape (i.e., Fig. 2), the pulse duration of 150 psec achieved above produces a 3 dB bandwidth of about 2.1 GHz; if $I_B(t)$ is assumed to be a square pulse, a 150 psec pulse produces a 3 dB bandwidth of approximately 2.9 GHz. Thus, at present the system of Fig. 1 is capable of performing stroboscopic scanning microscopy with a bandwidth in excess of 2 GHz. This system has been used for about one year on a variety of solid state device studies and has continued to perform satisfactorily.

Since contrast in an SEM secondary electron image can result from variation in the potential on the surface of a specimen, secondary electron emission can be used to measure time varying surface potential distributions. In previous work, we had demonstrated that the stroboscopic mode of time resolved SEM could be used to examine time varying potential distributions on the surface of semiconductor bulk effect oscillators; however, a clear demonstration of the frequency response capabilities was not given. Here we examine the surface potential as a function of time for a sinusoidal signal applied to a planar device of simple geometry. Figure 4(a) shows the particular sample chosen and the arrangement of the secondary electron collector relative to the sample. The sample consisted of a small chip of silicon with a voltage $V_s$ applied to evaporated film metal electrodes spaced about 40 $\mu$m apart. The chip was bonded to a transistor header which was connected to external equipment through miniature semirigid coax. The sample was held at approximately 45° to the incident primary beam which was focused onto the semiconductor surface between the two metal electrodes. The resulting secondary electron current was collected, detected, and amplified by the conventional combination of scintillator, light pipe, and photomultiplier. In a crude attempt to obtain a linear relationship between the collected secondary electron signal and the potential $V_s$, the voltage on the mesh of the secondary electron collector was varied until the plot of Fig. 4(b) was obtained. Although the collection scheme was linear only to within 20%, this layout sufficed to illustrate the time resolving capability of the stroboscopic mode. To test the stroboscopic technique at frequencies above 1 GHz, a microwave signal was applied to the planar sample and the setup of Fig. 5 was used to measure the surface potential as a function of time, $V_s(t)$. To provide synchronization between the incident primary beam pulse and the applied rf voltage, a portion of the rf signal (i.e., the dashed line in Fig. 5) was applied to the trigger input of a sampling oscilloscope (hp 1430A, 1425A, and 1411A) through a countdown box (hp 1104) and the sync output from the oscilloscope was used to trigger the primary beam pulse generation circuit of Fig. 1. The system was operated in a manner very similar to that previously used; the sampling oscilloscope was gated to sample only at the peak of the collected secondary electron signal and the vertical output
of the oscilloscope was applied to the Y input of an X-Y recorder whose X input was a voltage proportional to the difference between the arrival time of the primary beam pulse and the phase of the rf voltage at the sample surface. By continuously varying the delay of the Lumartron pulse generator, plots of the potential at the primary beam impact point vs time could be accurately and rapidly obtained.

Typical results are shown in Fig. 6 for applied voltages at the frequencies of 1.0, 1.5, and 2.0 GHz. The measured decrease in the collected secondary electron signal with frequency correlates with the expected frequency response assuming a triangular shaped primary beam pulse of 150 psec in width; this provides an independent confirmation to the measurements of Sec. II. The effect on the output signal of increasing the width of the primary beam pulse is shown in Fig. 7. Note the significant decrease in output signal when the 3 dB bandwidth of the stroboscopic system is decreased from 2.1 to 1.2 GHz by increasing the triangular shaped primary beam pulse from 150 to 270 psec in duration.

In the stroboscopic mode of time resolved SEM, the rapid deflection of the primary beam across an aperture has been shown to induce astigmatism at the target, resulting in a degradation of the spatial resolution.

![Fig. 6. The collected secondary electron current emitted from the surface of the device of Fig. 4(a) vs time. (a) The applied surface potential was set at 2.6 V (rms) and a frequency of 1.0 GHz while the relative photomultiplier gain was 1.00. (b) Surface potential of 1.6 V (rms) and 1.5 GHz and relative gain of 0.76. (c) Surface potential of 1.8 V (rms) and 2.0 GHz and relative gain of 0.96.](image1)

![Fig. 7. The effect of varying the width of the primary electron beam on the output of the stroboscopic SEM. The applied surface potential was 1.5 V (rms) in amplitude and at a frequency of 2.0 GHz. (a) Collected secondary electron signal vs time for an estimated primary beam pulse width of 150 psec. (b) Collected signal for an estimated primary beam pulse width of 270 psec.](image2)

However, it should be noted that this induced astigmatism is not a fundamental limitation on the spatial resolution in the stroboscopic mode. Either an optimum design of the traveling wave deflection plates and aperture system or an altogether different method of pulsing the electron beam should substantially reduce the effect of rapid chopping on the spatial resolution of the beam.

ACKNOWLEDGMENTS

The author gratefully acknowledges the valuable assistance of R. M. White. Also, the author appreciates the devices and equipment supplied by R. H. Haitz, T. Hsu, P. Magnusson, M. V. Schneider, and F. W. Voltmer.

---

* Work supported by the National Science Foundation under grant GK-2797.
† Present address: Department of Electrical Engineering, University of Minnesota, Minneapolis, Minn. 55455.
¶¶¶¶¶ For example, a 100 MHz, 1 kW sinusoidal signal applied to above system should produce primary beam pulses under 60 psec wide. This corresponds to a stroboscopic bandwidth of over 5 GHz.
¶¶¶¶¶¶ Application note 918, Hewlett-Packard Corp., Palo Alto, Calif.
¶¶¶¶¶¶¶¶¶¶¶ Several methods using secondary electrons for potential measurement have been devised which provide both high linearity and wide dynamic range. For example, see O. C. Wells and C. G. Bremer, J. Sci. Instrum. (Ser. 2) 1, 902 (1968), or N. C. MacDonald, Appl. Phys. Lett. 16, 76 (1970).