SPECIAL CRTS

7612D ELECTRON BOMBARDED SEMICONDUCTOR TUBE FOR HIGH-SPEED ANALOG–DIGITAL CONVERSION

The basic concept of the device is illustrated in Figure 19-1. An electron gun produces a ribbon beam which bombards a semiconductor target. The beam is focused by a cylindrical lens to form a flat ribbon-like beam which can be deflected over the target area. The target consists of a silicon chip containing a number of long diodes overlayed by a pattern of thick and thin metal in the form of a digital Gray code. A simplified version of the target is shown in Figure 19-2. The diodes are reverse biased and normally non-conducting. When the beam bombards a thin metal (window) area, it penetrates to the diode junction region and generates an output current. Due to the large number of electron hole pairs excited in the semiconductor, a considerable electron gain occurs in the target, on the order of 2000 for a 10-kV beam. In the thick metal regions of the target there is no beam penetration and no output signal.

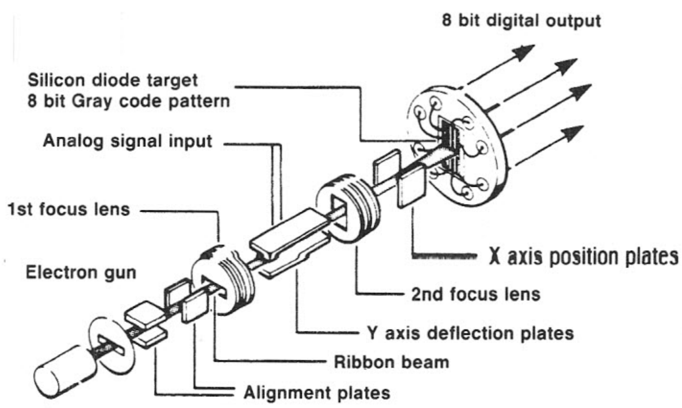

Figure 19-1

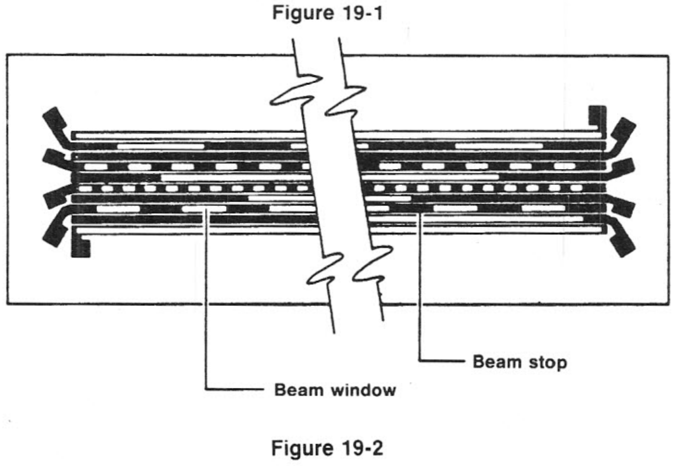

Figure 19-2

In operation the input analog signal is applied to the signal deflection plates and moves the beam up and down the target. In any position, some diodes will be on and others off. At the target, a parallel digital output code is thus generated which uniquely defines the beam position and hence the amplitude of the input signal. Since electron beams can be readily deflected at high speeds and diodes can be designed to give a fast response, the device is capable of giving high-speed conversions with good accuracy.

Electron-beam A/D converters were used in early pulse code modulation systems. The first tubes used a round beam which was scanned over a coded aperture plate. A single collector electrode behind the plate provided an output signal when the beam was positioned over an aperture. The signal to be coded was applied to vertical deflection plates while the beam was scanned horizontally. This provided an output in serial form. The speed was limited but sufficient for audio signals. A later version of the tube employed a ribbon beam with separate electrodes for each bit of the code. This gave a parallel output word and enabled operation at conversion rates to 10 MHz, which is suitable for handling video data.

The use of a semiconductor target fabricated with planar technology, as described in this section, allows the coding pattern to be integrated with the beam collector. In addition, the high electron gain possible with electron-bombarded silicon diodes increases the sensitivity of the device considerably and enables operation at much higher conversion rates.

Semiconductor targets have been used successfully in a variety of amplifier tubes and in a scan converter. An electron-beam sampling device which uses a semiconducting target as a detector has also been described.

ELECTRON GUN DESIGN

The electron gun was designed to produce a ribbon-like beam which could be focused to a fine line image on the target. This beam shape is necessary to address all diodes simultaneously and give a parallel read-out signal. The beam potential was chosen to give the best compromise between target gain (which increases with beam voltage) and deflection sensitivity (which decreases). Previous studies have shown that 10 kV is an optimum choice for a monoaccelerator gun of this type. This beam voltage results in a net gain of about 2000. For an output signal of 5 mA from each diode, the beam current per diode is then 2.5 μA. Since only a portion of the beam lands on an active area of the target, the total beam current required is about 50 μA. In order to obtain 8-bit resolution with a practical target size, the focused beam linewidth was designed to be 0.0012 in. (30 μm) full width at half maximum (FWHM). This size enabled the required beam current to be obtained with a reasonable gun length.

A ribbon beam is formed in the gun by using beam apertures which are slots rather than round holes as in most guns. The lenses formed by these apertures produce a focusing action in only one axis, the axis which is perpendicular to the slots. Theoretically, this is true only if the slots are of infinite length, but an aspect ratio of length to width of at least 6:1 gives an adequate approximation. The triode section of the gun forms a line crossover which is subsequently focused into a line image at the target. A second slot lens perpendicular to this first focus lens confines the spread of the beam in the other axis and improves gun efficiency. The potential on this second lens is set below that required for a fully focused condition, to obtain the required beam profile as shown in Figure 19-3.

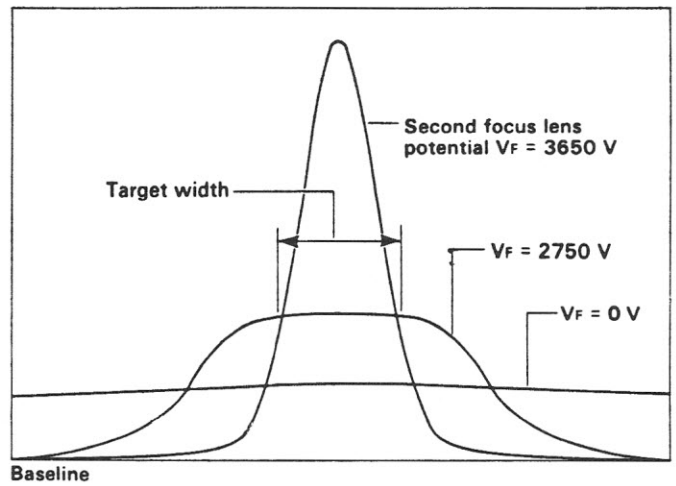

Figure 19-3

The gun contains four sets of deflection plates. They are the x and y axis alignment plates, the x axis position plates, and y axis signal plates. The x and y axis alignment plates correct for triode misalignment by centering the emitted current distribution on the respective beam limiting apertures at the focus lens entrances, thus maximizing beam current. The x position plates are used to center this distribution on the target. The signal plates, of course, carry the analog signal which is to be digitized.

The sensitivity of the signal deflection plates is nominally 23.5 V/scan. To achieve this value with a 10 kV beam required fairly long plates (2.75 in. or 7 cm) which limits the frequency response due to electron transit time. However, for a 100 MHz signal bandwidth, solid deflection plates gave an adequate response, and it was not necessary to use a traveling-wave deflection system.

The ribbon beam was found to be more susceptible to distortion from fringing fields in the deflection system than is the case with a round beam. To avoid these distortions, an adequate plate width and good shielding was necessary. The extra plate area increased the plate capacitance, but it was within acceptable limits for the signal amplifier.

An external magnetic coil is mounted in the entrance region of the deflection plates. It rotates the ribbon beam into precise alignment with the target. This location allows the ribbon beam to be rotated without producing an unacceptable amount of scan rotation. The scan alignment is maintained with the aid of alignment pins which align the target assembly to the electron gun.

The mechanical stability of the gun is an important consideration in a digitizing tube since small movements of the gun with respect to the target upset the calibration. Microphonic effects cannot be tolerated as these produce oscillations in the output signal. To avoid these problems, additional supports were provided for the gun to ensure that it was ruggedly mounted in the envelope.

TARGET DESIGN

The target was required to supply an output signal of 5-10 mA per diode into a 50 Ω load. To keep the capacitance low for a fast response time, the target was made as small as possible, the limit being determined by the electron beam width. The smallest window opening, i.e., that on the diode providing the least significant bit (LSB) of the output code, needs to be large enough to allow most of the beam to penetrate the diode, otherwise the LSB output will be smaller than that of the other diodes. Since the beam size in the y axis is on the order of 0.0011 to 0.0013 in. (28 to 33 um) (FWHM), the window opening in the LSB diode was made 0.0018 in. (46 um) which will pass about 90% of the beam.

The target pattern is in the form of a Gray code since this gives more accurate output than straight binary in the device configuration. With the Gray code only one transition occurs at a time and each transition is equivalent to a change of one LSB.

An 8-bit Gray code requires 8 diodes with 64 cycles in the LSB diode. This sets the diode length or vertical scan at 230 mils. An additional continuous diode is located on each side of the coded area for alignment purposes, making a total of 10 diodes per die. The size of the target die is 0.25 x 0.04 in. (0.635 x 0.102 cm).

The target is fabricated using silicon planar technology. A cross section of a target die is shown in Figure 19-4. An n-type expitaxial layer is grown on a (100) oriented n+ silicon substrate.

The wafer is oxidized and openings for the diode are cut in the oxide by photolithography. Diodes are then formed by a boron diffusion. The junction depth is very shallow, about 0.25 um, to minimize the loss of beam energy in the p region. An aluminum film approximately 1-um thick is deposited over the target and photoetched to form the Gray code pattern. Finally, a thin (500A) aluminum film is deposited over the diode to provide a low resistance contact for the diode current. Each diode is surrounded by n+ channel. The purpose of this is to isolate the diode thus improving stability, reducing leakage currents, and minimizing crosstalk between diodes.

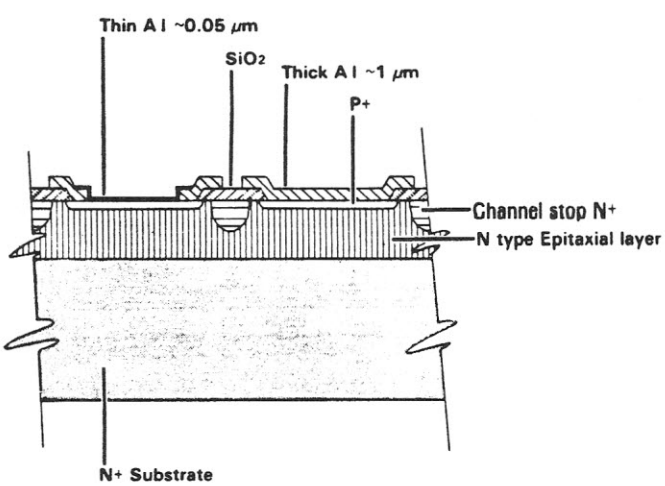

Figure 19-4

The width and resistivity of the epitaxial region was chosen for the best compromise between a low diode capacitance and high level of current saturation. Output limitations on EBS diodes have been discussed in the literature. In general, limitations occur when the electric field in the depletion region of the diode falls below the minimum value required to maintain electron drift velocity (approximately 1.6 x 10^4 V/cm. Modifications to the electric field can occur due to space charge associated with the carriers that produce the diode current or to a reduction of the diode voltage through large signal swings. In the digitizer device, the output signal of 250 mV has negligible effect on the diode bias (11.5 V). The main restriction is thus due to space charge which limits the current density that can be generated in the diode before the response speed is affected.

In Figure 19-5 the epitaxial thickness to maintain a minimum electric field of 10^4 V/cm is plotted against the epitaxial layer resistivity. Also shown are the corresponding values for the maximum current density and the diode capacitance. The value of epitaxial resistivity used for the design is 15Ω/cm giving an epitaxial thickness of 4.5 μm, a target capacitance of 2.32 x 10^3 pF/cm^2, and a maximum current density of 750 Acm.

There were two main points to consider during the target mounting design. First, it was important to have the silicon chip containing the diodes accurately positioned with respect to the beam, particularly in regard to rotational alignment. If the ribbon beam is not orthogonal to the diodes, errors in the output code can occur. The second concern was to have an adequate thermal path to dissipate the power generated in the target.

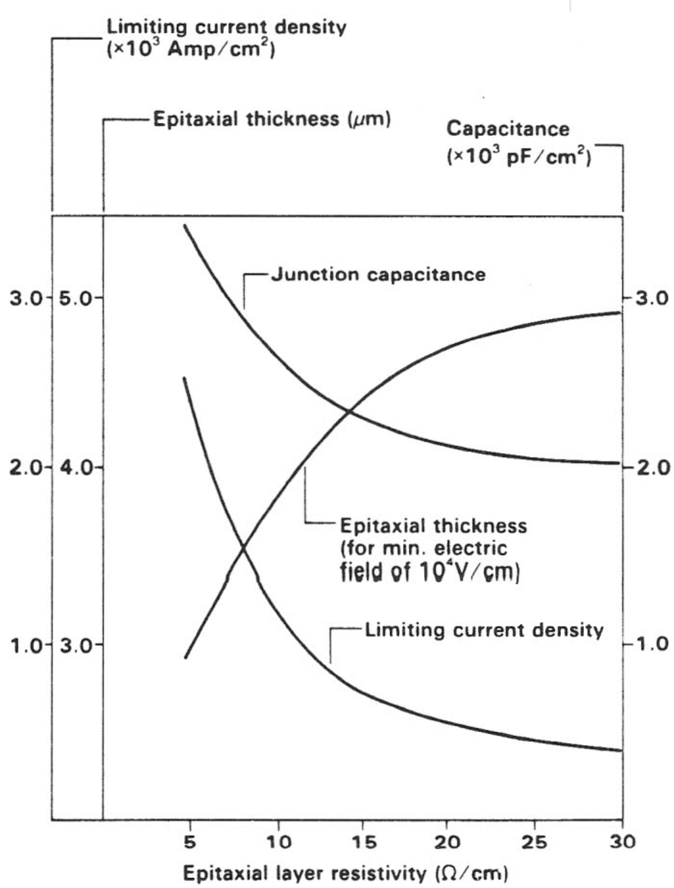

Figure 19-5

In most applications the exact position of the die is not critical, consequently, the equipment available for die attach is not capable of accurately aligning the die on the substrate. To overcome this problem, the die is attached to a separate carrier consisting of a ceramic substrate brazed to a kovar platform. This carrier is then welded to the target header in a special fixture which enables the diodes to be accurately positioned with respect to indexing pins on the header. These pins align the header with the gun during final assembly.

Another advantage of the ceramic substrate is that it allows thin-film coplaner transmission lines to be used for connecting the diodes to the header feed-through pins, thus avoiding the extra inductance incurred when using long bonding leads. The feed-throughs and transmission lines were designed to have a characteristic impedance of 50 Ω to match the input impedance of external comparator circuits.

Since the beam occupies less than 2% of the target area, power is dissipated in only a small part of the target at any instant. The worst case is when the beam is stationary on the target in a position where all the diodes are turned on. In this case power is concentrated in a small area and can reach power densities of 760 W/mm^2. Under normal operation about 1.1 W are dissipated in the target due to the beam and induced current in the diodes. In addition, an external comparator circuit which is attached directly to the header dissipates 4.8 W and further compounds the cooling problem.

Both alumina and BeO ceramic were tried as substrates. Measurements of the temperature rise at the diode surface were made using an IR microscope. For these measurements special die were used in which a small area could be forward biased to simulate the power dissipation effects of the beam. Tests were carried out with both internal and external power applied. With and without forced air cooling, to determine the temperature rise expected on the device when mounted in an instrument. The maximum temperature difference between the hottest spot on the diode surface and the outer edge of the header was 57° C/W for an alumina substrate and 44° C/ for BeO.

Although BeO had the best thermal results, it gave poor parts yield due to shorts on the coplaner transmission lines which occurred during the brazing cycle. Since the alumina gave adequate results and was easier to work, it was decided to use this material. The maximum temperature on the outside of the target header in an instrument environment is expected to be about 70° C which would result in a maximum diode junction temperature of 127° C.

PERFORMANCE

The performance of the digitizer determines how accurately the output code represents the input signal. It is convenient to consider this in two parts: (a) the static or low-speed capability and dynamic or high-speed limitation. The various factors which determine the performance of the device are considered in the following sections.

A. Static Characteristics

The dc linearity of the device is determined by the signal deflection plate linearity and the accuracy of the code pattern on the target. Since the electron gun is a 10-KV monoaccelerator with a maximum deflection angle of less than 1.6° , non-linearity in the deflection is expected to be very small, of the order of 0.03%. This is confirmed by the linearity measurement described below.

The pattern in the Al film on the target is produced using photolithographic techniques and can be made quite precise. Small variation can be expected from run to run, but these are carefully controlled and checked on each run. Measurements are made on the length of the window opening in the thick metal of the LSB diode. A tolerance of $\pm 2\%$ is specified for the window which ensures that the transition in the code pattern are in the correct position within ± 0.09 LSB. Generally targets are well within this tolerance.

To verify the linearity of the device, measurements of the deflection voltage at each LSB transition were taken on several tubes. A typical result is shown in Figure 19-6, which indicates the voltage required to deflect the beam between adjacent transitions as a function of the position on the target. Note that there is a difference of 10 mV between the average positive and the average of the negative going transition. This indicates that the length of the windows on the LSB diode in this target is 5% smaller than the space between windows. Ideally these would be equal. The difference is equivalent to 2.4 μm which is within the tolerance of 4 μm specified for target processing, and represents a displacement of the code transition points of 0.05 LSB. Non-linearity due to deflection would result in a reduction of the voltage between transitions at each end of the target. This effect is masked by the other variation in our measurements.

A more serious problem with the EBS digitizer is non-alignment of the sheet beam with the target and changes in the beam shape. Some of the problems that can occur are shown in Figure 19-7.

Static beam rotation is shown in Figure 19-7(a). This occurs when the target is not aligned with the vertical axis of the gun. Since the target pattern is designed for a ribbon beam which is perpendicular to the diodes, a significant rotation of the beam (2° or larger) with respect to the target can result in errors in the output code. Care is taken to ensure that this alignment is as close as possible during assembly and small errors are corrected with an external beam rotation coil.

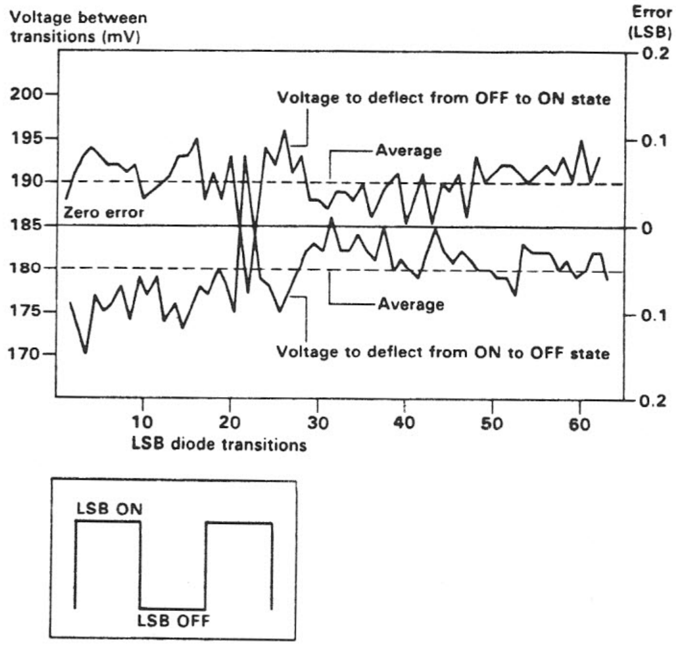

Figure 19-6

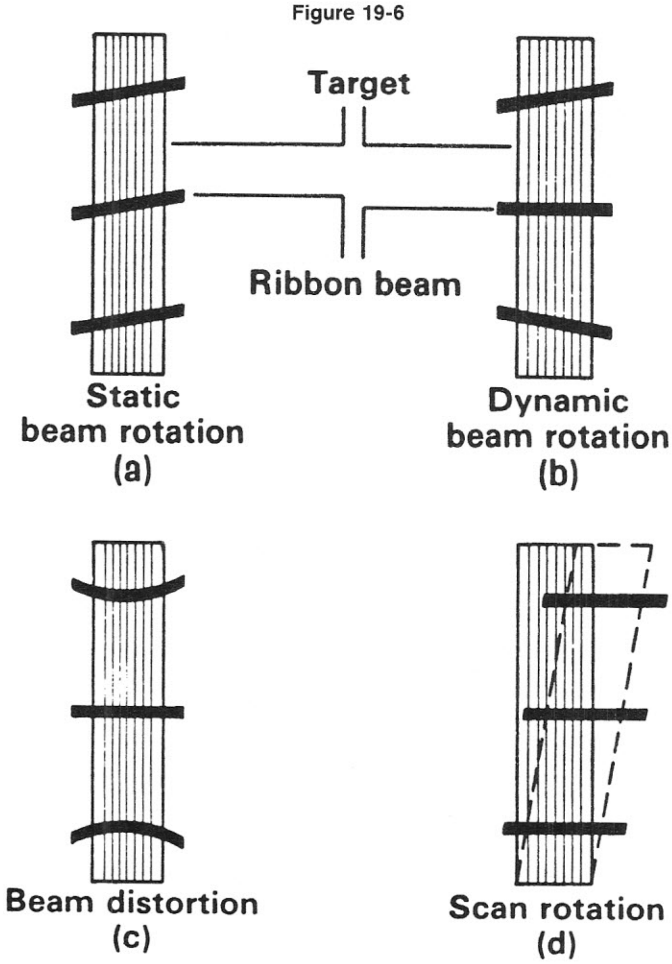

Figure 19-7

Dynamic rotation occurs when the angle between the beam and the target changes with deflection as shown in Figure 19-7(b). This effect can occur when the deflection plates are not parallel. The deflection sensitivity then varies across the plates resulting in a rotation of the beam. This rotation is increased by the second slot lens since the long axis of this lens is perpendicular to that of the beam. In this case, the slot lens magnifies the angular error in the alignment of the ribbon beam axis to a line perpendicular to the long axis of the lens. The rotation coil used to correct static rotation is not suitable for correcting dynamic rotation. However, hexapole fields will correct this defect. The action of an electrostatic hexapole field is illustrated in Figure 19-8 which shows the magnetic fields acting on the ribbon beam for three positions of the deflected ribbon beam.

Both electromagnetic and electrostatic hexapoles were tried. The electrostatic one worked particularly well. These systems were not used in the final version of the gun because dynamic rotation was held to less than 1° by maintaining a close tolerance on deflection-plate spacings and strength of the second slot lens.

Curvature of the beam, Figure 19-7(c), can be caused by fringe fields along the signal deflection plates. This effect is minimized by making the signal deflection plates sufficiently wide.

Scan rotation results in a horizontal shift in the beam with vertical deflection as shown in Figure 19-7(d). Small amounts of scan rotation are generally not a problem provided the horizontal profile of the beam has a constant amplitude for a distance somewhat greater than the target width. If the profile is not flat the amplitude of the signal from the diode can vary with vertical position. Scan rotation is kept to a minimum by careful alignment during assembly as explained above.

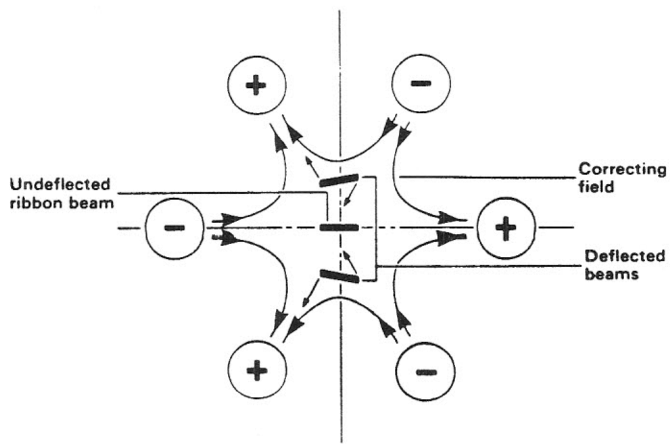

Figure 19-8

If the beam is free from curvature [Figure 19-7(c)], beam rotation can be determined from the transition point of the various diode signal as the beam is scanned across the target. Figure 19-9 shows that LSB signal and the signal from the 2nd and 3rd bit diodes. Transition points of the higher order bits should occur at the peaks of the LSB signal. Shifts from the true position can be measured on an oscilloscope and used to determine the rotation angle. The standard measurement on the device is made on the 2nd and 3rd bit signal. For the particular geometry used in the target, the rotation angle ϕ is given by

$$\phi = \tan^{-1}[(2/3)(S/B)]$$

Where S is the shift from the true position and B is a reference equal to 2 cycles of the LSB signal.

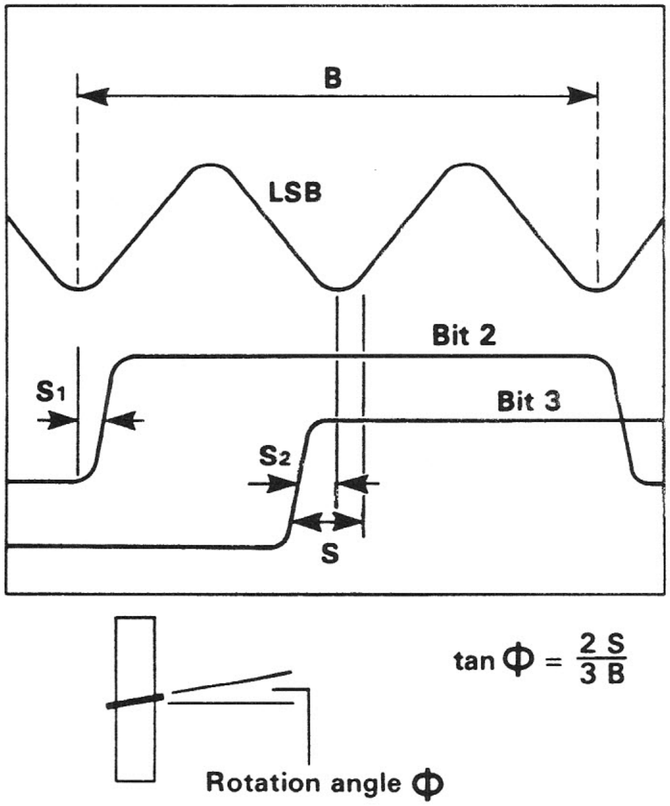

Figure 19-9

In the above discussion, the main types of beam distortion have been described. In practice, additional perturbation in the beam shape are sometimes present which do not fit these categories. Extending the method used for measuring beam rotation, an estimation of the beam shape at various points on the target can be made from the position of the transition of the higher order bits compared to the LSB signal. This measurement assumes that the target pattern is accurate and errors are due to the beam alone. In Figure 19-10, the beam shape in a sample tube is plotted at several places on the target using this method, the vertical scale in the vicinity of each plot is enlarged for clarity.

It can be seen that the beam has a static rotation (of about 1.6°) which is fairly constant over the length of the target. This can be corrected with a rotation field. In addition, there are small perturbation in the beam giving a maximum error with respect to an average straight line of 0.1 LSB.

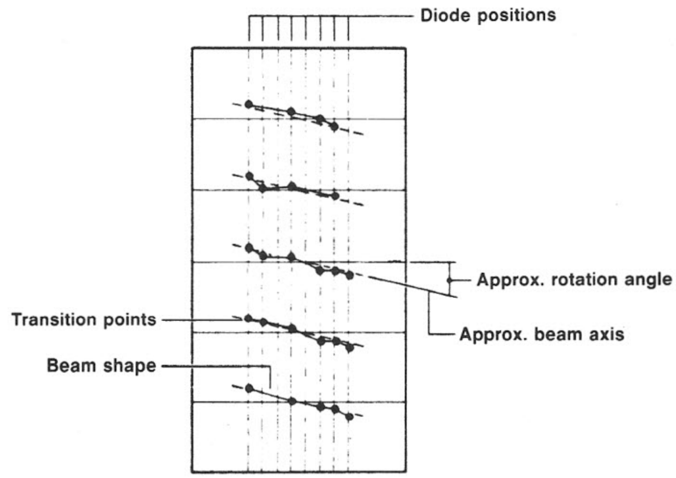

Figure 19-10

The effects of dynamic beam rotation on the output code were investigated using a computer simulation program which was designed to estimate the performance of the digitizer in an operating system. The model used for the program assumed that the beam remained straight, had zero rotation at the target center and the rotation increased linearly with deflection towards the target ends as shown in Figure 19-7(b). The results indicated that a maximum rotation of 2° could be tolerated before errors in excess of 1/2 LSB appeared in the output code.

The overall performance of an A/D converter is determined by the accuracy of the output code. This is generally done by comparing the output against a standard reference code. To check the performance of the EBS digitizer, a digital test circuit was built which is shown in a simplified block diagram in Figure 19-11.

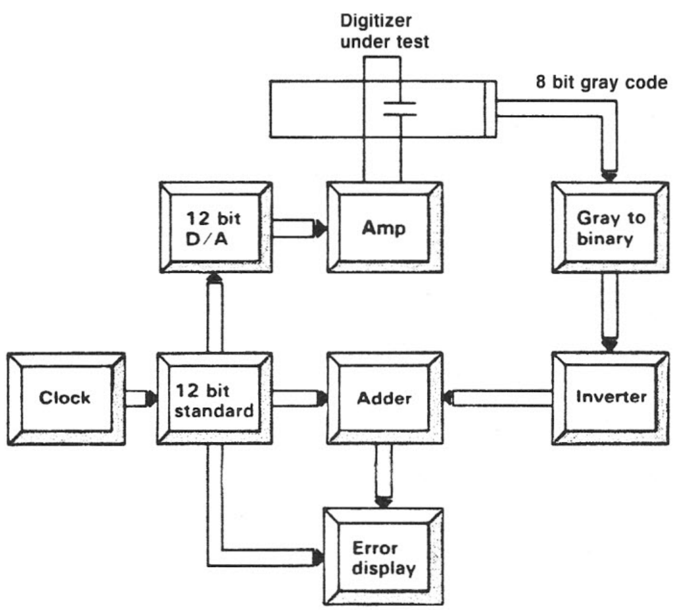

Figure 19-11

The test circuit is built around a standard 12-bit binary code generator which can be cycled from 0 to 4096. This standard generator is used to drive a 12-bit D/A converter to provide a ramp for applying to the deflection amplifier of the digitizer. The output Gray code is converted to binary, inverted, and added to the standard binary to produce an error signal. A comparison is made at each transition of the output code. The error signal is then a measure of the difference between the actual output transition point and the ideal transition as represented by the standard. Since the 12-bit standard has 16 transition between successive points on the 8-bit code, the acutal output transition points can be located to 1/16 of an 8-bit LSB. An error plot can be obtained by using the error signal as an ordinate and the standard 12-bit binary as an abscissa. These signals can be applied to an oscilloscope to give a continuous display. A clock rate of about 100 KHz is sufficient for a flicker-free display but slow enough to avoid settling time errors in the circuit.

The error display has proved useful in setting up the digitizer. Adjustment in signal gain and dc position have a marked effect on the error signal and can be readily optimized with the aid of an error display.

B. Dynamic Characteristics

The frequency response of the device is dependent of the rise time of the diodes and output circuit at the target and the bandwidth of the deflection system.

The main factor which limits the accuracy of the device at high speed is the response of the LSB diode. This is because the LSB output signal contain much higher frequency components than the applied signal. For the case where the input is a full amplitude sine wave, the maximum frequency component in the output from the Nth-bit diode (f_N) max will occur at the zero crossings of the sine wave where the beam deflection velocity is greatest. For the Gray code pattern, which has 2^{N-2} windows, it is related to the input signal by

$$(f_N)\,\mathrm{max} = 2^{N-2}\,\pi\, f_{sig}$$

where N is the number of resolution bits and f_{sig} is the input signal frequency. For the LSB diode on the present device where $N = 8$, the maximum frequency in the LSB signal is approximately 200 times that of the applied signal.

As the input frequency is increased, the amplitude of the LSB output signal is reduced when the diode response is exceeded, until a point is reached where the output code is effectively decreased from 8-bit to 7-bit accuracy. At still higher frequencies the next higher bit drops out giving a 6-bit code. Thus, accuracy is progressively lost as the signal frequency is increased.

The basic response of the target is determined by the diode capacitance C and the output impedance R. The rise time is approximately 2.2 CR which for typical device values of C=5 pF and R=50 ohms gives a value of 550 ps. For the situation in which the beam is continuously deflected over the target (e.g., for a sine wave input) the amplitude of the signal from the Nth-bit diode, V_N, at high speed is given by

$$V_N = V_N \sqrt{\frac{[1-\exp(-t_N/CR)]}{2\{1-1/2[1-\exp(-t_N/CR)]\}}}$$

in which V_N is the maximum (low speed) value and $t_N = \left(1/2 \int N\right)$ the dwell time of the beam in each open window of the diode. The signal will have a dc component equal to $V_{N/2.}$ Using this expression, the decrease in the LSB signal at higher frequencies was calculated and is shown in curve A of Figure 19-12.

A more complete model of the output circuit takes into account the inductance of the lead bond wires, the impedance of the coplaner waveguide on the target substrate and the capacitance of the output feed-through. An equivalent circuit is shown in Figure 19-13.

The frequency response of this model was estimated using a computer simulation of the circuit and is shown in curve B of Figure 19-12. Measurements of the frequency response of the target and output circuit were made by observing the signal from the LSB diode on a sampling oscilloscope as the beam was swept along the target. By varying the beam deflection speed the relationship between frequency and amplitude of the signal can be determined directly from the scope display. A typical result is shown in Figure 19-12.

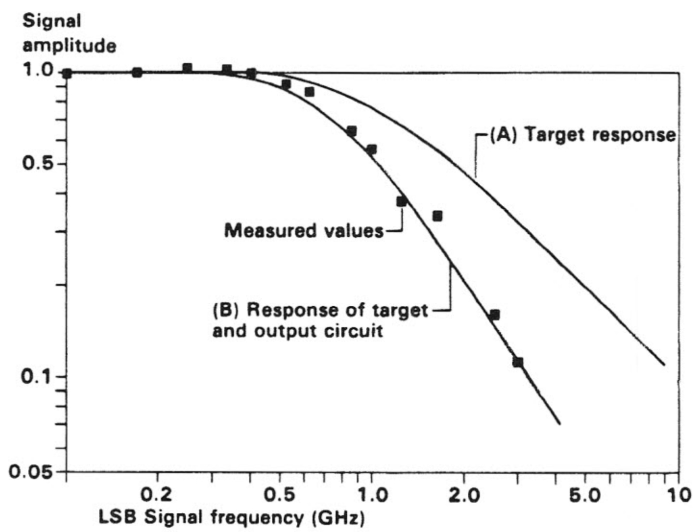

Figure 19-12

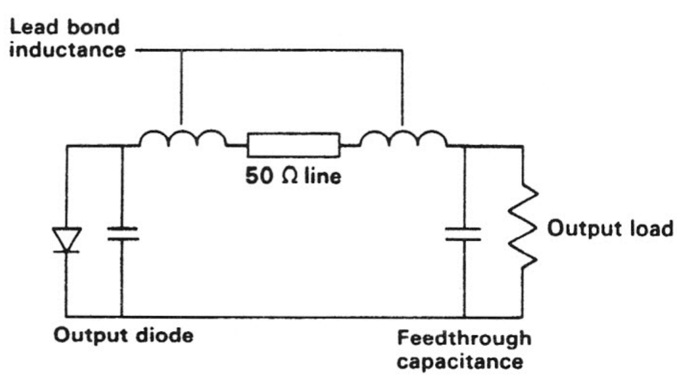

Figure 19-13

The minimum useful output signal depends on the value required for reliable operation of the comparator circuits which detect the target output. The comparator reference is normally set at a voltage which is the value about which the LSB output oscillates. Error in comparator circuits can be of the order of a few mV, so that 10 mV changes about the reference value can be easily detected. To estimate the performance of the digitizer, a minimum LSB signal of 25 mV peak to peak will be used, which is 1/10 that of a typical low-speed signal amplitude of 250 mV. The dc component is assumed to be at the comparator reference of 125 mV. From Figure 19-12, the frequency at which the LSB signal falls at 1/10 maximum is 3 GHz. The equivalent maximum full-scale sine wave at the input is obtained from Eq (2) and is 15 MHz for 8 bit, 20 MHz for 7 bit, and 60 MHz for 6-bit resolution.

If the beam is at rest on the target, the dc value of the LSB output can vary from 0 to V_N. When the beam is deflected, the dc value changes to $V_N/2$ within a few LSB cycles. Since the beam cannot be deflected to maximum speed instantaneously, the dc value of the LSB signal is normally at the $V_N/2$ value by the time the maximum speed is reached.

Exceeding the frequency response of the deflection system results in a decrease in amplitude of the high frequency components of the signal being digitized at the target. Since the deflection plates form part of the output circuit of the signal amplifier, the total system needs to be taken into account when considering the bandwidth limitations due to deflection. One parameter that can be considered separately is the limitation due to electron transit time within the deflection plates. The plates are 2.75 in. long which gives a transit time of 1.18 ns for a 10-KV beam. This results in a reduction of deflecting power for signals above 100 MHz. The 3-db point in the rolloff due to transit time occurs at 450 MHz. At 100 MHz, deflection sensitivity has decreased by 2.1%.

RELIABILITY

Life tests lasting several thousand hours have been carried out on a number of devices. The results indicate that the main aging process is an increase in the reverse leakage current in the target diodes due to bombardment by the electron beam. Prior to operation diode leakage is normally less than 5 nA. During the first few hours of operation, the leakage increases to several hundred nanoamps. It then remains at this level for the remainder of the life test. The reverse breakdown voltage remains fairly steady throughout the operation.
The increase in leakage is believed to result from charge created in the oxide and at the silicon-oxide interface by electrons and X ray from the electron beam. This charge alters the electric field at the junction edge leading to increased leakage. By providing additional shielding for the junction edge, it should be possible to reduce the radiation effects of the beam. However, the leakage levels normally observed are several orders of magnitude below the signal level and do not interfere with the normal operation of the device.

High voltage arcs either in the tube or the external circuits produce high-level transients which can damage the diodes in the target. The result is usually a decrease in the diodes reverse breakdown voltage and a considerable increase in leakage current which causes a shift in the baseline of the output signal. Damage can be avoided by isolating the target bias circuit from potential transients, by providing safe return paths for arc currents, and by limiting the energy that can be dissipated in an arc. If adequate precautions are taken, arcing can occur without damaging the target.