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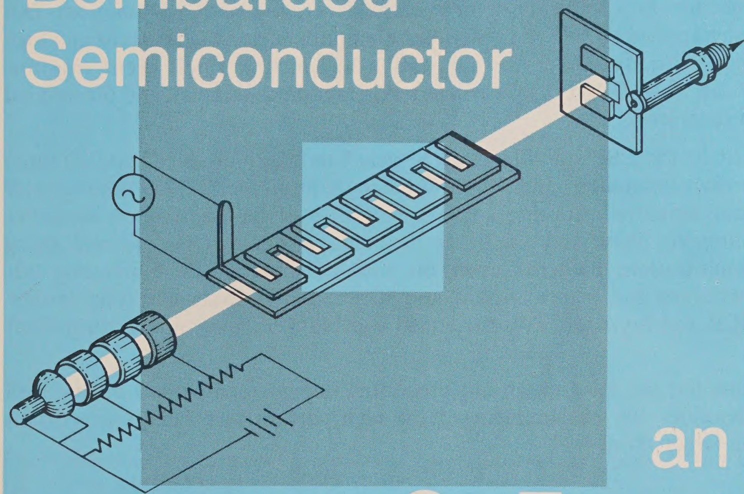
WATKINS-JOHNSON COMPANY
Tech-notes

Developing the Electron Bombarded Semiconductor



an On-Target Amplifier

Information is a multi-faceted term in today's scientific world. The means by which we obtain information pertinent to our particular interests are also multi-faceted.

Why a new information vehicle?

This first edition of "Tech-notes" is the beginning effort on the part of Watkins-Johnson to assist you to zero in on the specifics of todays surging technology.

It is our intent to produce an informative and technical periodical published bimonthly and circulated without charge to educational institutions, engineers, managers of companies or government agencies, and technicians. Each issue will feature an interesting and self instructive article dealing with the technique of applied engineering and science, presented in a format whereby the reader can proceed directly to the material of interest.

We hope you find "Tech-notes" a source in keeping abreast of the developments in todays technology, and an asset towards expanding quality performance in your area of personal interest.

The Editor

The key to the development of many new devices is the proficient merging of various technologies. It is this reason, the combining of the vacuum and silicon semiconductor technologies, that has materialized the Electron Bombarded Semiconductor (EBS) device. With most all the vacuum-semiconductor design and processing problems solved, reliability results of EBS device operation are already exceeding 8,000 hours.

The EBS principle makes use of an externally modulated electron beam to control the current injection in a semiconductor such as a reverse-biased pn junction. This principle is being applied to RF and video pulse amplifiers, and high current and high voltage switches. Also, future device application will include single event real-time samplers, very fast A to D and D to A converters, function generators, and picosecond rise-time pulse generators.

Figures of merit of the EBS amplifier show a "gain bandwidth product" 10,000 times greater than a cavity amplifier, and a "power bandwidth product" 1,000 times greater than a transistor amplifier. Another advantage of EBS is the use of fewer elements, therefore, minimizing phase and amplitude distortion, reducing rise-time, and giving high linear amplification. Switches using the EBS principle are demonstrating sub-nanosecond switching and higher current amplification than avalanche type devices, such as, the SCR and thyristor, with the added capability of being quickly turned-off after turn-on.

This issue points out the most important processing improvements made on the EBS device, and describes the development of the high performance radiation resistant semiconductor target diode.

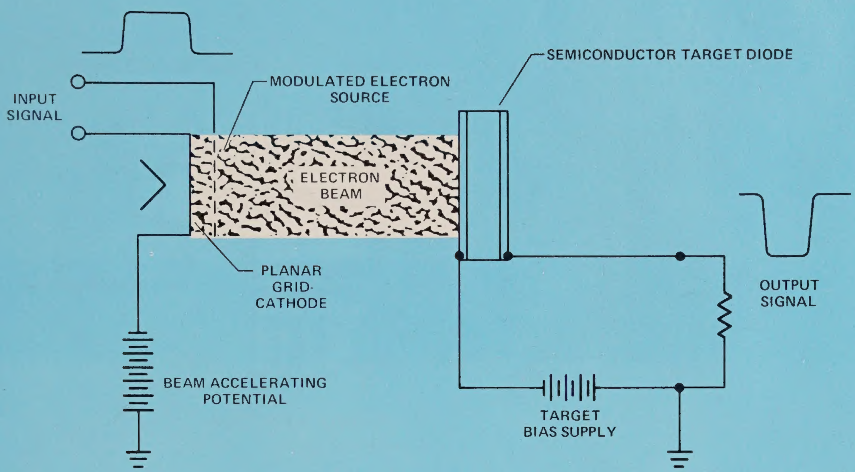


Fig. 1 Elementary EBS device showing a density modulated electron beam and a single back-biased target.

Bombarding a Back-Biased Diode
As the name implies, the EBS device utilizes electrons originating from a thermionic cathode to bombard a back-biased semiconductor diode in a vacuum. The EBS is first and foremost a vacuum tube; however, the most critical portion of the device from a reliability standpoint is the back-biased semiconductor diode. Power devices require high electric fields and power dissipation in the semiconductor, together with a relatively high electron bombarding energy.

History—Technical Problems to Resolve
During the past twenty-five years EBS devices were sporadically investigated by a number of laboratories*. A review of these investigations provides extremely useful historical information, but, very few solutions to the technical problems encountered are to be found. Significant problems early EBS developers had to overcome were:

- Including a semiconductor with a thermionic cathode in the same vacuum envelope, and to a less degree, including a thermionic cathode with a semiconductor in the same vacuum envelope.
- Bombarding the semiconductor with energetic electrons.
- Existence of high electric fields at the vacuum-semiconductor interface and the semiconductor diode junction.
- Dissipating the high thermal heat generated in the semiconductor target.

All the semiconductor targets used were silicon and the vacuum tube portion was of the conventional ceramic-metal glass-metal construction. Both oxide and impregnated cathodes were used in the fabrication. The basic development philosophy was to adapt existing technology wherever possible to obtain better performance, therefore, higher reliability.

Two EBS Device Configurations—Planar Triode and Deflection Modulated
The simplest EBS device construction is the planar triode, Fig. 1. Electrons produced by a planar thermionic cathode

* Investigations are found in references 1 through 6.

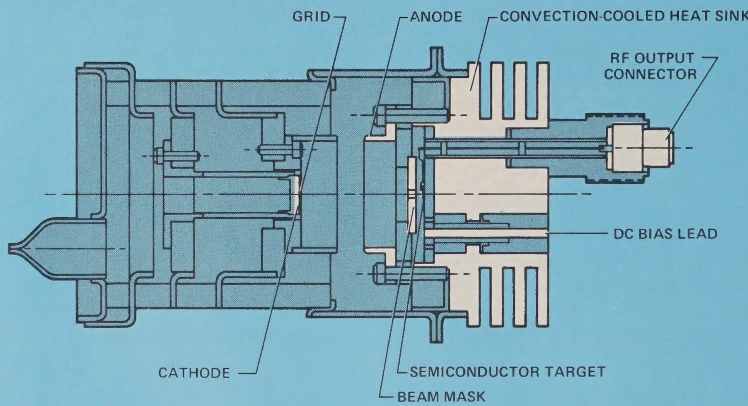


Fig. 2 Cross-sectional view of a WJ-3653 Planar triode EBS high-voltage short-pulse modulator device.

are modulated by a close-spaced planar grid and accelerated by a high voltage power supply at energies of 12 to 15 keV. The energetic electron beam then irradiates one surface of the reverse biased diode, either p-n junction or Schottky. Current flow in the external circuit is in proportion to the charge injected into the diode with the amplified signal appearing across the load.

The WJ-3653 is an example of a high voltage modulator EBS device capable of producing 400 volts output across a 100 ohm load with a 3 nanosecond risetime. Fig. 2 is a cross-section of the WJ-3653. The thermionic cathode is in relatively close proximity to the semiconductor target and the electric field accelerating the electron beam extends into the target region.

The second EBS device configuration is the deflection modulated, Fig. 3. This configuration differs from the planar gridded device in that the target is located further away from the electron gun. A narrow electron beam is projected through the traveling-wave RF deflection structure. The modulated beam deflection is proportional to the signal on the deflection structure, causing a variation in the number of electrons that separately illuminate one of the semiconductor diodes (shown at the right). The positive half of a RF cycle appearing across the load is due to the illumination of one of the diodes, while the other half of a RF cycle is produced by the illumination of the other diode.

A typical deflected beam amplifier is the WJ-3650 and is shown in Fig. 4. The WJ-3650 amplifier produces ±100 volts into a 50 ohm load with a 1 nanosecond rise-time; alternately 50 watts of CW, or 200 watts of pulsed RF power can be produced within a bandwidth from dc to 300 MHz. The device shown is conduction cooled; however, higher power versions require liquid or forced-air cooling. The beam mask shown in front of the semiconductor target (at right) allows the electron beam to illuminate only the active area of each diode. This device is

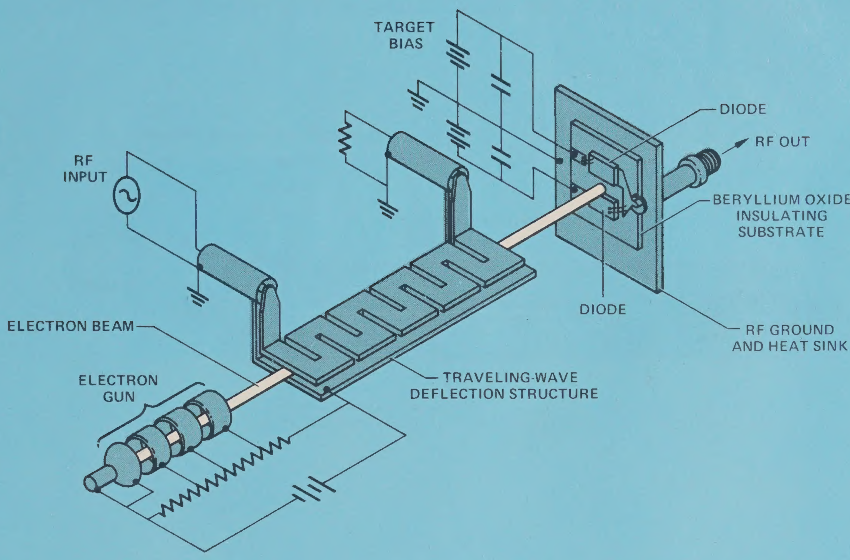


Fig. 3 A deflection modulated EBS amplifier with a traveling-wave beam deflection structure and two Class-B connected diodes.

used primarily for highly efficient linear RF and video amplifiers.

Reliability Improvements in Semiconductor Targets

The early semiconductor target diode used a bare junction mesa structure. Reverse breakdown characteristics of this type of diode degraded as a result of just placing it into a vacuum and biasing it with a high electric field. Developing a device for high power and high efficiency requires operating the target diode as close as possible to the avalanche breakdown, and any decrease in the avalanche voltage will seriously degrade the EBS performance capability.

Passivation of the target diode junction region has eliminated this type of degradation due to a vacuum environment and the presence of the thermionic emitter. Since vacuum-compatible materials are now being used for the diode, the presence of the semiconductor diode has no detrimental effect on the performance of the thermionic emitter. However, voids in the diode back-bonding do pose a threat to the vacuum integrity since the trapped gas in the void remains at atmospheric pressure, or approximately 10 to 11 orders of magnitude higher than in the vacuum. A small passage from a void will cause a continuous flow of gas into the vacuum tube. Voids in the diode back-bonding are essentially being eliminated by improved processing techniques.

At the present time EBS devices are processed through a bakeout process at 350°C and cathode activation with essentially no change in the diode reverse breakdown characteristics. The only limitation being experienced is the presence of the germanium-gold eutectic alloy required for the diode back bonding. The diode bonding material requires the nominal bakeout temperature not to exceed 350°C, thereby preventing a thorough degassing of the tube during bakeout. It has been found necessary to degas the target structure further by means of electron bombardment with an appendage ion pump attached prior to final vacuum seal-off. Some experiments with tin-gold eutectic are being tried; however,

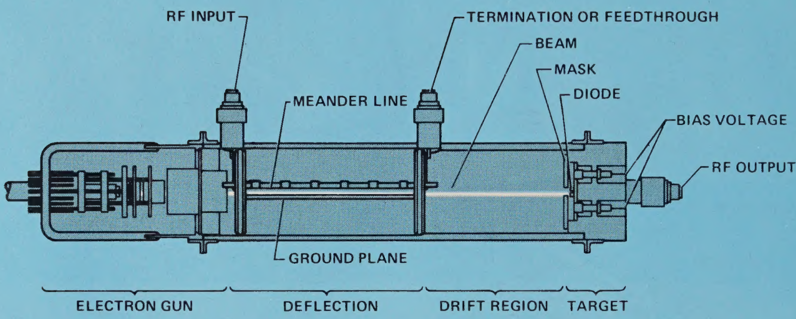


Fig. 4 Cross-sectional view of a WJ-3650 deflection modulated EBS amplifier. The electron gun is on the left, the traveling-wave deflection circuit in the center and the semiconductor target on the right.

the incidence of bonding voids is still very high with the processing techniques available to date.

Oxide Passivated Planar Target

A simple planar target diode bombarded by energetic electrons is shown in Fig. 5. All but the diodes active portion is shielded from direct beam illumination. Secondary electrons and X-rays are generated in a region that is out of the direct beam optical path, but can strike the planar diode target as illustrated. Both electrons and X-rays cause the electron-hole pairs to be created in the oxide. Though the electrons migrate out of the oxide, the holes will not migrate at or near ambient room temperature. The positive charge trapped in the oxide causes the reverse breakdown voltage to decrease. Typically, thermal oxide passivated diodes having reverse breakdown voltages between 300 and 400 volts degrade to a stable reverse breakdown voltage of approximately 120 volts after a few hours of electron beam bombardment. The result of this decrease in reverse breakdown voltage is that thermal oxide passivated planar diodes are not suitable for high power devices.

Radiation Hardened Target

Development of a more reliable semiconductor diode led to the radiation-hardened EBS target, Fig. 6. A 2 micron (μm) thick phospho-silica glass layer is deposited on top of the thermally grown oxide. Electrons and X-rays still cause ionization in the passivation layer but the traps produced are not as close to the silicon oxide interface as in the planar structure. The decrease in breakdown voltage is also less severe than in the planar target.

Example of I-V curves for a reversed biased diode pair before and after electron beam irradiation is shown in Fig. 7. The reverse voltage has degraded to 320 volts after irradiation by 13 keV electrons for a period of some 20 hours.

The reverse breakdown characteristic become completely stable after the first few hours of irradiation. The charge traps can be removed from the passivation layer by annealing the diode at 100 degree C for about 10 hours. Also, as

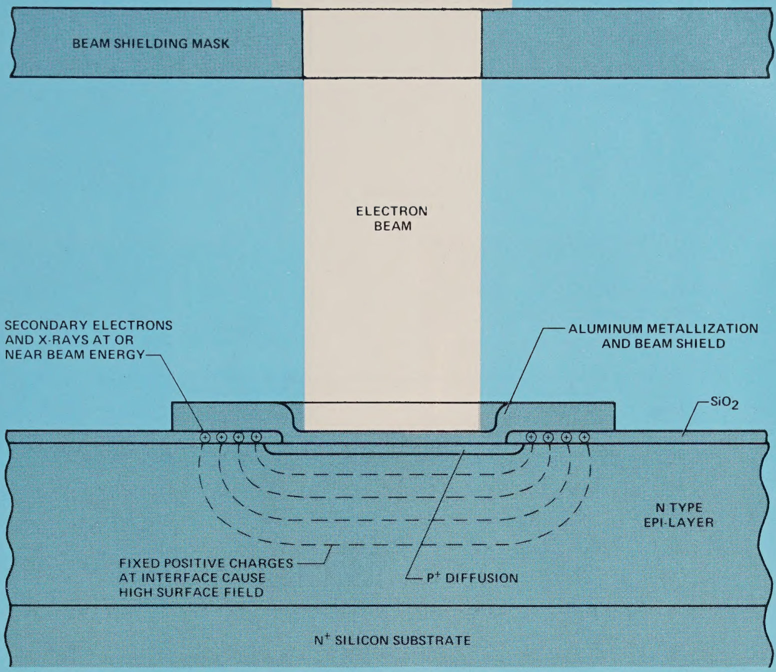


Fig. 5 A simple planar EBS semiconductor target diode illustrating the bombardment of the passivating oxide by energetic electrons and X-rays.

described by Norris*, there are no other degradation effects caused by irradiation with electrons at energies of 20 keV or less. Although high diode temperatures are undesirable from some performance and reliability views, high temperatures actually reduce the reverse breakdown degradation effects due to electron bombardment.

Integral Metal Beam Shielded Target

Another development that significantly reduces the electron irradiation effects is the integral metal beam shield semiconductor target, Fig. 8. A number of metal pillars are formed on a metal rim around the periphery of the diode, then a large metal frame is plated on top of these pillars. This frame overlays and protects the high field region around the junction periphery from bombardment by stray electrons and X-rays. Typical diode parameters used in one of the Watkins-Johnson integral beam shielded deflection modulated EBS devices is shown in Table 1**

Temperature Effect on Performance

Electro-migration of the surface metallization, the top contact metallization and the formation of intermetallics in the back-bonding are enhanced by high diode temperatures. Also, performance is degraded at elevated temperature by a reduction in the carrier saturation velocity, and by an increased resistivity of the top contact metallization and the highly doped p+ and n+ diode regions.

Diode operating temperatures are significantly reduced by the development of a void-free back-bonding. The computed maximum diode temperature rise of a typical pair of 1 X 2.5 mm^2 diodes is approximately 80 degrees C with a diode dissipation density of 20 watts per mm^2. Thus, the thermal impedance of a diode pair is approximately 0.8 degrees C per watt.

A unique void elimination technique involves gold and copper plating the beryllium oxide (BeO) substrate, followed by metallization of the die with titanium, moly, and gold. Next, gold-germanium

* Investigation of Norris is found in reference 7.

** Tables appear on page 11.

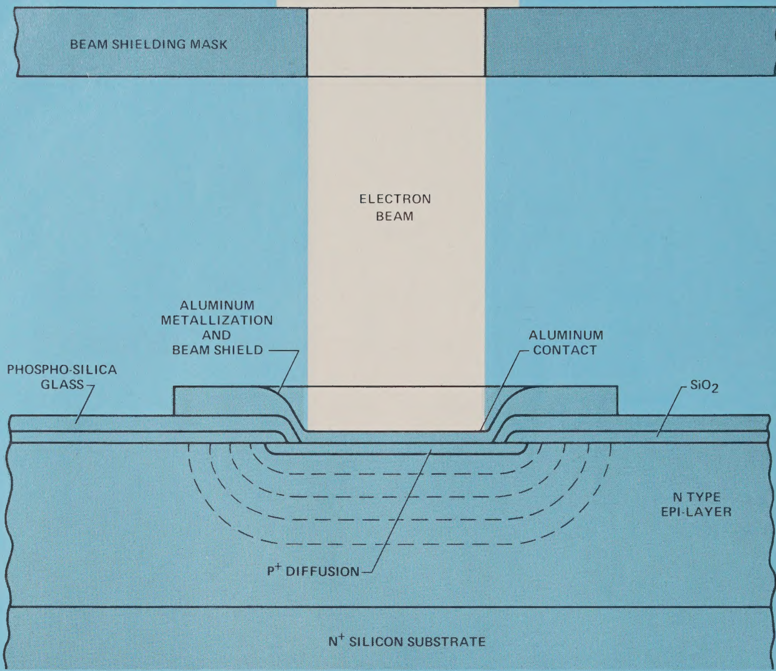


Fig. 6 Cross-section of a radiation hardened diode showing the incident electron beam and beam shielding mask.

(Au-Ge) eutectic preform is placed between the die and the substrate, and the parts are heated in forming gas until the preform melts and thoroughly wets both substrate and die. X-rays taken of a diode bonded to the BeO substrate can indicate the presence of voids, and can even be used to quantify the size and number of individual voids.

As a result of these and other improvements, EBS power devices can now operate at higher peak and average powers, and operate more reliably. A large number of devices, both CW and pulsed, have been operated continuously for thousands of hours without failure.

Life Tests and Reliability Determination
Previous life test hours were accumulated on CW and RF amplifiers operating with target diode dissipation densities of 20 watts per mm^2 or more. Today, however, life tests are being carried out on a number of different EBS devices such as, CW and RF amplifiers, and high current and high voltage modulators.

Eight CW amplifiers and four pulse modulator devices are currently being life tested at Watkins-Johnson and by the U.S. Army at their ECOM Evans Laboratory. Each device is exhibiting significant performance capabilities, including those designated as ONR life test devices; that is, it is not a portion of a device. The high voltage modulator, WJ-3653, produces 350 to 400 volts across a 100 ohm load with a 3 nanosecond risetime. The RF and video pulse amplifier, WJ-3650, produces 100 volts peak into a 50 ohm load with a 1 nanosecond risetime. Both the ONR and WJ-3650 devices are deflected beam Class-B amplifiers so each amplifier has two individual target diodes.

RF Amplifier Test Summary
The eight Class-B deflected beam CW, RF EBS amplifiers on continuous life test are operating at a diode dissipation density of 20 watts per mm^2 or greater. Test data is summarized in Table 2. To date there has been no failures, or degradation in performance, either for the total device or for the individual semiconductor target in the devices. The resultant mean-time-between-failure (MTBF)

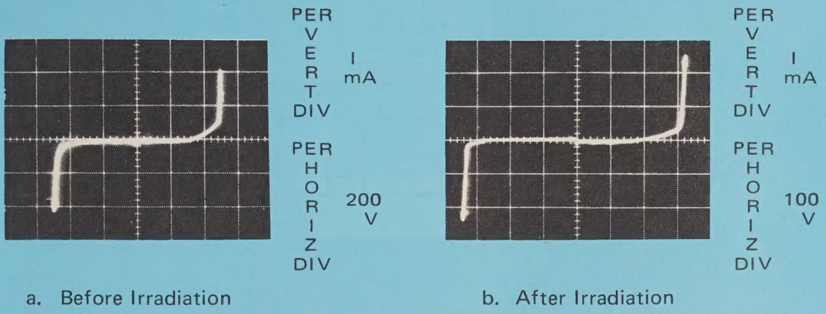


Fig. 7. Reverse bias I-V characteristics of a diode pair before and after electron beam irradiation. Note the horizontal scale deflection change from 200 to 100 volts per division.

and failure rate (FR) are data-limited and not device reliability limited. Note that one device has passed 7900 hours and the cumulative test time is over 33,000 hours. The total MTBF is over 37,000 hours and the FR is less than 27,000 bits (1 bit $= \frac{10^9}{\text{MTBF}}$).

Pulse Testing Results

In addition to the above amplifier tests, four WJ-3653 modulators are now under pulsed life test sponsored by NAVELEX, and the data is summarized in Table 3. The total operating time of the four devices is now above 10,000 hours and the computed MTBF is over 11,000 hours with a 60 percent confidence level.

Continuing Improvements

Watkins-Johnson Company and its semiconductor diode supplier, the Signetics Corporation, are continuing reliability improvements. More than one device has operated at diode densities in excess of 40 watts per mm^2 for a number of hours without degradation. One device even operated for a few minutes at 95 watts per mm^2 diode dissipation density. In the latter device, the actual total dissipation for the two diodes was 132 watts and the dissipation of each of the diodes was 66 watts. Although W-J cannot recommend basing a long life design on 95 watts per mm^2 dissipation density, it is believed that a safe design dissipation density at the present time is 40 watts per mm^2.

Summary and Conclusion

Individual EBS devices are exhibiting in excess of 8000 hours of reliable operation. A diode MTBF of 75,000 hours has been established for CW, RF amplifiers operating at diode dissipation densities of 20 watts per mm^2. Integral beam shielded passivated planar diodes significantly reduce degradation of reverse breakdown characteristics for electron bombardment energies up to 15 keV. Diode dissipation densities of 20 watts per mm^2 and higher are being demonstrated. To date, no incompatibility between the thermionic emitter, the vacuum and the semiconductor is being encountered.

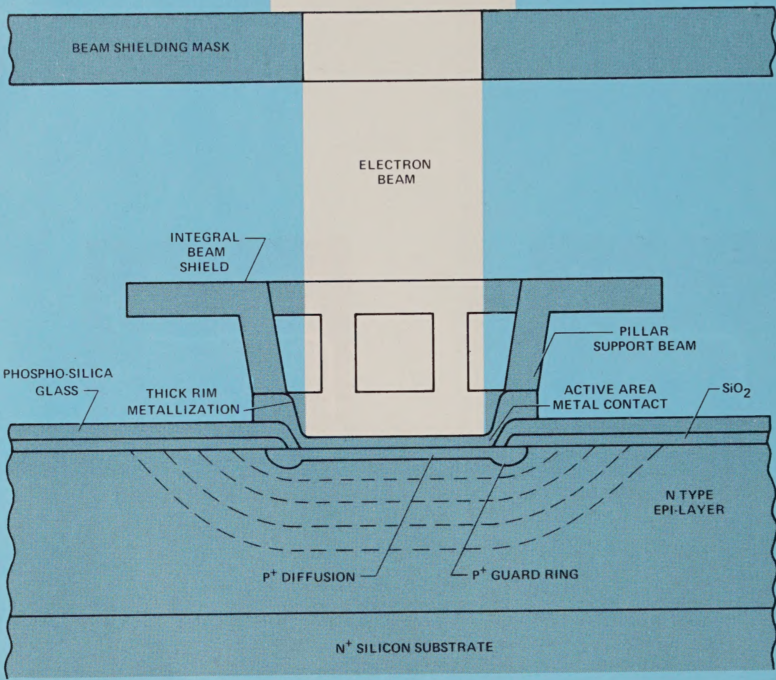


Fig. 8 Radiation hardened diode using a pillar supported integral metal beam shield to protect the thermally grown oxide and phospho-silica glass from beam bombardment.

Since EBS devices are still in their infancy, it goes without saying, that a considerable amount of reliability work remains. In the future, higher temperature back-bonding material is going to be required, along with diodes which are immune to electron and X-ray irradiation with energies of 20 to 30 keV. It is important to note, that every technical problem encountered to date has been solved by relatively straightforward modifications of existing technology. This trend is expected to continue.

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Diode Material (Silicon)		**Surface Passivation**	
EPI-thickness	30 μm	Oxide	1 μm
EPI-resistivity	50 Ohm-cm	Phospho-silica glass	2 μm
Total diode thickness	250 μm		
Junction Properties		**Diode Metallization and Bonding**	
P+ depth	3000 Å	Active area metal,	Nickel-silicide
Guard ring depth	3.5 μm	Thickness	400 Å
Doping method, material	diffusion, boron	Thick rim metal	Ti-Pt-Au
Active area/diode	2.5 mm^2	Integral beam shield.	Au
		Diode mounting substrate	BeO ceramic

Table 1. Typical semiconductor target parameters for an integral beam shielded EBS amplifier.

Device Type	Devices on CW Test	Time (Hours)	Diode Dissipation Density	Remarks
ONR	1	7,944	20 W/mm^2	Tests Continuing
	1	6,560		
WJ-3650-3	2	4,899	20 W/mm^2	Tests Continuing
	1	4,109	25 W/mm^2	
	1	3,369		
	2	1,067	30 W/mm^2	
Total Device Reliability				
CW Test Time		33,814		
MTBF		37,500		At 60% Confidence
FR		26,600 bits		
Individual Diode Reliability				
CW Test Time		67,628		
MTBF		75,100		At 60% Confidence
FR		13,300 bits		

Table 2. EBS RF Amplifier Reliability Summary.

Device Type	Devices on Pulse Test	Time (Hours)	Test Condition	Remarks
WJ-3653	1	3,077	4% Duty Cycle	Tests Continuing
	1	2,720	at 350 volts	
	1	2,449	peak into an	
	1	2,310	100 ohm load	
Total Device Reliability				
Pulse Test Time		10,556		
MTBF		11,700		At 60% Confidence
FR		85,300 bits		

Table 3. EBS Pulse Modulator Reliability Summary.

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WATKINS-JOHNSON

Manufacturing and Office Locations

United States

SALES OFFICES

CALIFORNIA
Watkins-Johnson
3333 Hillview Avenue
Palo Alto 94304
Telephone: (415) 493-4141

Watkins-Johnson
831 South Douglas Street
Suite 131
El Segundo 90245
Telephone: (213) 640-1980

DISTRICT OF COLUMBIA
Watkins-Johnson
700 Quince Orchard Road
Gaithersburg, Md. 20760
Telephone: (301) 948-7550

FLORIDA
Watkins-Johnson
325 Whooping Loop
Altamonte Springs 32701
Telephone: (305) 834-8840

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Watkins-Johnson
700 Quince Orchard Road
Gaithersburg 20760
Telephone: (301) 948-7550

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Lexington 02173
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Suite 200
Fairborn 45324
Telephone: (513) 426-8303

TEXAS
Watkins-Johnson
9216 Markville Drive
Dallas 75243
Telephone: (214) 234-5396

International

ITALY
Watkins-Johnson Italiana
S.p.A.
Piazza G. Marconi 25
00144 Roma-EUR
Telephone: (6) 59 45 54
Telex: 63278
Cable: WJROM-ROMA

GERMANY, FEDERAL REPUBLIC OF
Watkins-Johnson
Manzingerweg 7
8000 Muenchen 60
Telephone: (089) 836011
Telex: 529401
Cable: WJDBM-MUENCHEN

UNITED KINGDOM
Watkins-Johnson
Shirley Avenue
Windsor, Berkshire SL4 5JU
Telephone: (7535) 69241
Telex: 847578
Cable: WJUKW-WINDSOR

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