Technical articles

Semiconductors inside tubes make high-performance rf amplifiers

Rf power amplifiers and modulators with unprecedented voltage-rise-time and gain-bandwidth capabilities will soon be obtainable, now that it's possible to build reliable, long-lived electron-bombarded semiconductor devices

by David J. Bates, *Watkins-Johnson Co., Palo Alto, Calif.*

☐ Electron-bombarded semiconductor (EBS) devices, which are essentially semiconductor diodes in the same envelopes as modulated electron beams, are now coming on the market as radio-frequency amplifiers and modulators that far outperform either vacuum tubes or semiconductors acting on their own. The idea is not new—an EBS device, after all, is just a photodiode illuminated by a high-energy electron beam instead of light—but only in the past few years have the problems of reliability and lifetime been solved.

No EBS device is in actual systems use yet, but their unusual features will soon make them an attractive alternative in many high-power, wideband digital and analog systems. For instance, their gain-bandwidth and power-bandwidth or voltage-rise-time capability is 100 to 10,000 times greater than that of existing competitive devices. A high-voltage modulator has produced 800 volts output with less than a 1-nanosecond rise time, for a dv/dt of nearly 10^{12}V/second. A high-current modulator has produced 100 amperes output with 2-ns rise (and fall) time, for a di/dt of 50,000 A/microsecond.

Besides an electron gun and diode, an EBS device contains an rf input section and an rf output assembly (Fig. 1). The gun is biased negatively with respect to a semiconductor diode, either a conventional pn junction or a Schottky diode. The electron beam, which illuminates the diode with electrons having energies in the 12- to 15-kilovolt range, is controlled by a pulse from the rf input section. The rf output assembly takes the signal from the diode, which is reverse-biased well below avalanche threshold in order to keep leakage currents low when the electron beam is turned off.

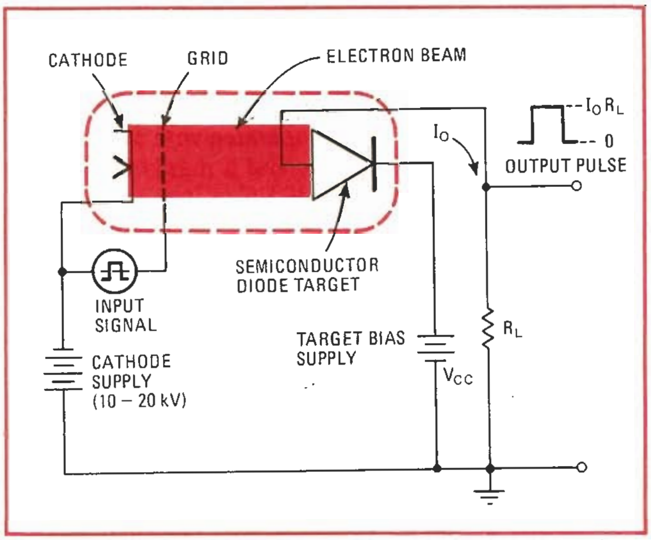
While the electron beam is on, however, electrons penetrate the depletion region of the diode (Fig. 2) and generate hole-electron pairs—one pair for each 3.6 electron-volt loss (more or less) of incident electron energy. This results in a current gain, from electron beam to diode current, of 2,000 or greater. The diode current then is applied to a load to develop the output pulse.

Three types

Figure 1 shows the most basic kind of EBS device. Known as the density-modulated type, it has some of the characteristics of a vacuum-tube triode. Since its output current is related to the grid voltage by an approximate three-halves power law, it is not used for applications that need linearity. However, the density-modulated device has a transconductance per unit area of cathode that is about 1,000 times greater than in a conventional planar-grid triode. This gives it much greater gain-bandwidth or voltage-risetime characteristics and makes it excellent for modulator applications.

A second type of EBS device is deflection-modulated (Fig. 3). Here, a traveling-wave modulation structure deflects the beam to illuminate a diode, and the amount of diode current is proportional to the deflection voltage. In an actual device, a deflection mask is inserted in front of the diodes to collect electrons when no input signal is applied. Highly linear amplifiers can be built with this technique. With two target diodes, the device can be operated in a highly efficient class-B operation—half of the input sine wave would deflect the beam in one direction and illuminate one diode, and the other half of the sine wave would illuminate the other diode.

The deflection-modulated device has no analog in ei-



1. Grid control. One type of electron-bombarded-semiconductor (EBS) device is similar to a vacuum triode. It uses a control grid to modulate the electron beam and hence the diode current. The output, taken across a load, can be of either polarity.

ther the vacuum-tube or semiconductor realm, so its performance cannot be compared with that of an existing device. However, it has achieved 50 watts linear rf output over a dc-to-300-megahertz frequency range.

A third type of EBS device creates a density modulation of the beam at the diode by modulating the electron velocity and then allowing the electrons to drift over a suitable path length. However, this type device seems not to offer as immediate applications as the first two types and has remained relatively undeveloped.

From concept to reality

The major difficulties in developing an EBS device arise from the need to put a semiconductor device with a high electric field at its surface into a vacuum envelope with a thermionic cathode. This can produce mutual contamination problems between the diode and the cathode, while the high temperatures required for the vacuum-tube process can affect the semiconductor diode's reverse breakdown voltage. Similar breakdown problems are caused by the high electric field at the interface between diode and vacuum. Then, too, bombarding even a passivated semiconductor with energetic electrons creates positive-charge traps. Finally, simply operating the diode at a high level of power dissipation means a lot of heat must be removed.

Early EBS devices used bare-junction mesa diodes, but the reverse breakdown voltages of these diodes quickly deteriorated during operation. Surface passivation with a thermal oxide over the junction region corrected this difficulty, but the charge traps continued to degrade the breakdown voltage. The effect was particularly evident in p-on-n diodes, which, unfortunately, are preferable for rf devices, because they have higher carrier drift velocities than the n-on-p type.

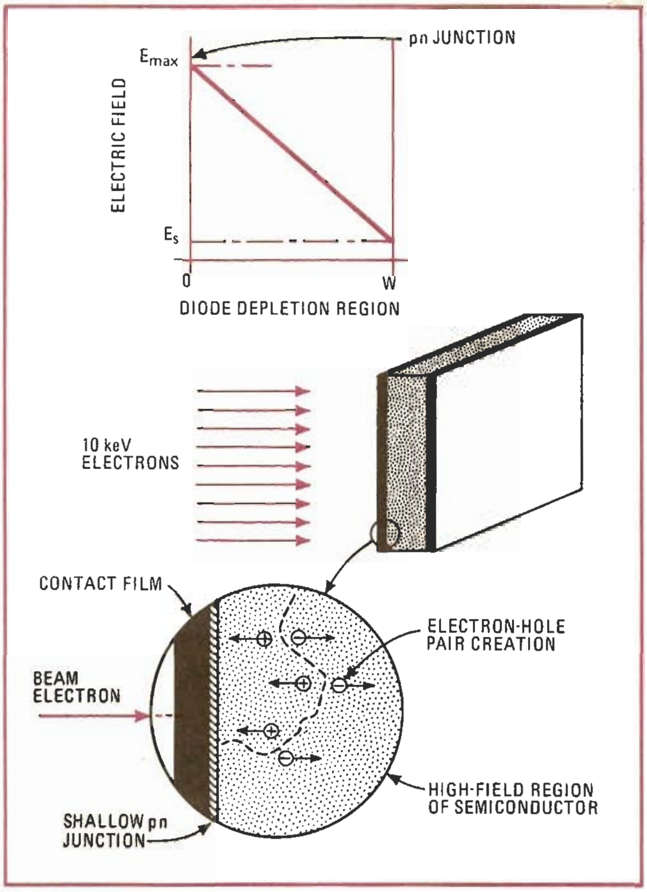
The problem was solved with a radiation-hardened passivated planar diode developed in association with Signetics Corp. This diode has a thick deposit of phosphosilica glass over the thermal oxide, and conventional beam-lead processing methods are used to form a metal electron-beam shield slightly above the surface of the oxide-glass passivation layer. The shield is located directly above the junction of the planar diode (Fig. 4).

Thermal problems were solved by attaching the diode to a heat sink by a method of silicon-gold void-free bonding. Such a diode can be operated with about 50 W continuous-wave output power and a maximum rise in diode junction temperature of 100°C or less.

How reliable?

The two elements that will wear out first in the EBS device are the semiconductor diode and the thermionic cathode. Still, cathode life is expected to be greater than 30,000 hours, and diode life should ultimately be many times the cathode life.

Several deflection-beam rf power amplifiers are on cw life test at Watkins-Johnson. As of June 24, 1974, two of these have accumulated 12,600 and 11,210 hours, respectively, with no change in operating characteristics. Eight devices have operated for 70,160 hours at diode dissipation densities between 20 and 35 W/mm^2 without failure, resulting in a mean time to failure of 78,000 hours at a 60% confidence level. Since each device contains two diodes, the total diode operating time is 140,300 hours at an MTTF of 156,000 hours, or about 17.8 years at a 60% confidence level.



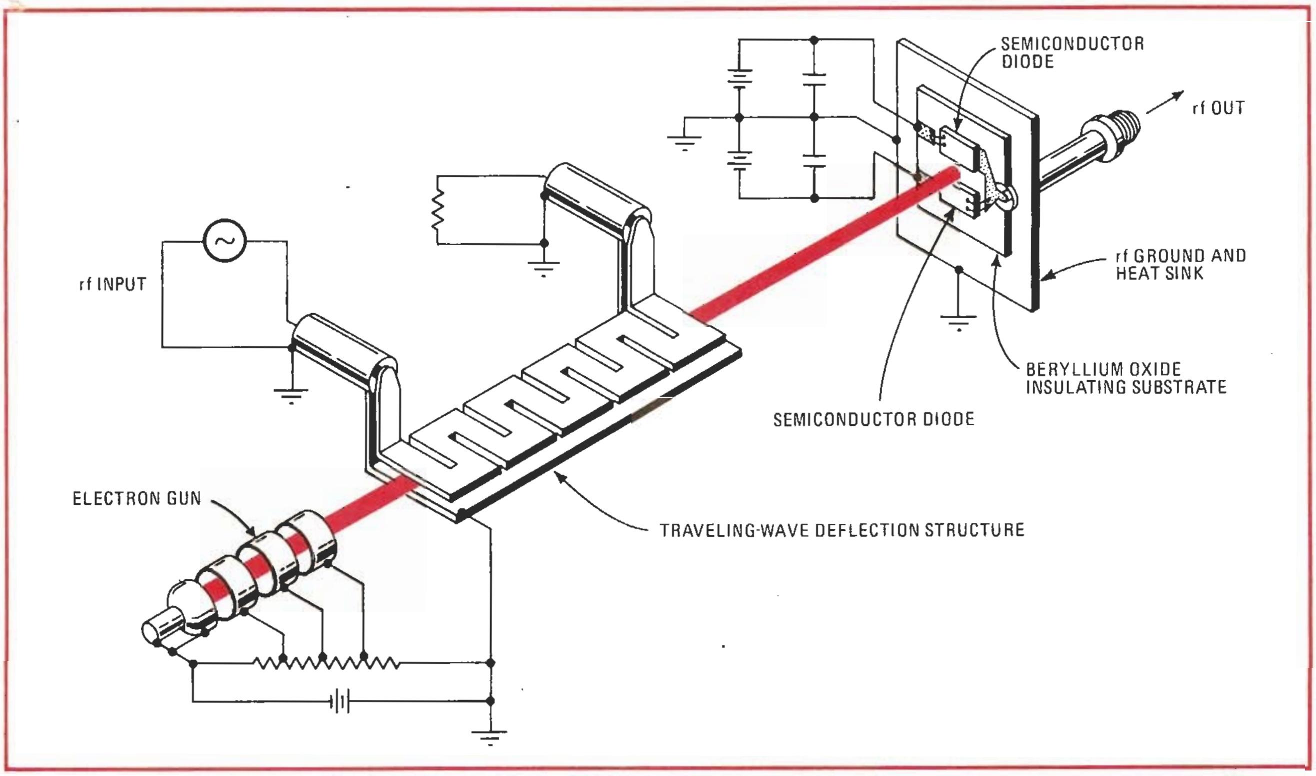
2. Close-up. When high-energy electrons strike a reverse-biased diode, they create electron-hole pairs in the diode depletion region. The high electric field then sweeps carriers out of the region to the output circuit. Result is current multiplication.

In addition, four high-voltage modulators have completed 22,350 hours with one failure for an MTTF of 10,900 hours at 60% confidence level.

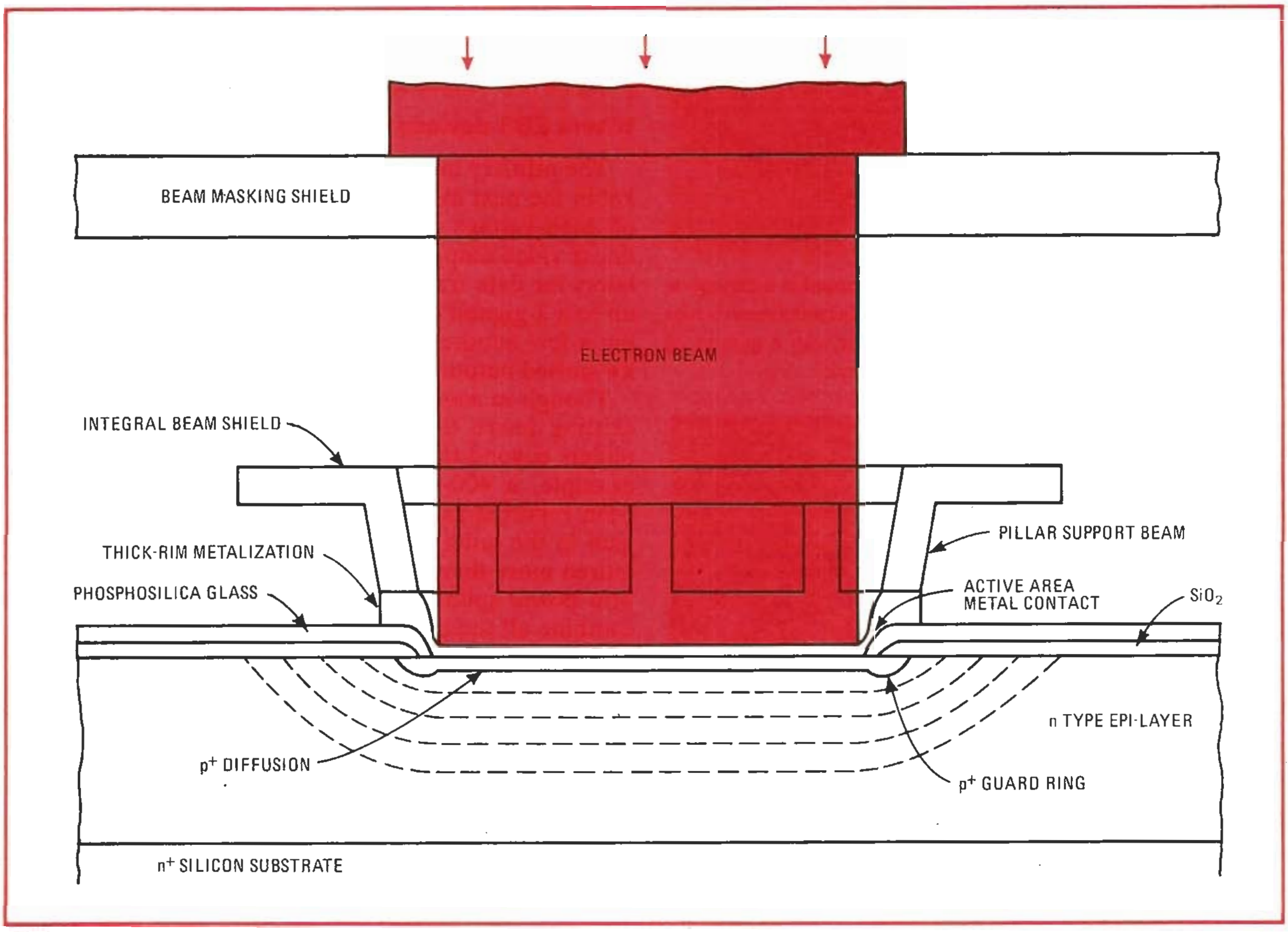
A good selection

Various versions of the density and deflection-modulated devices have been developed. Examples are: single-target-grid-controlled, density-modulated devices, which can be operated either Class C or Class A, and deflection-modulated amplifiers with either single targets for Class-A and Class-C operation or dual push-pull connected targets for Class-B operation.

In a planar-grid density-modulated device, for example, on-off signal ratios greater than 100,000 have typically been measured. This unit, which can be operated up to a 4% duty factor, provides 400-V output with 12-V input into a 100-ohm load, and a total rise time of 4 ns has been achieved (measured from the 10% point of the input waveform to the 90% point of the output pulse). This performance makes the device desirable for many fast-pulse modulator uses, such as optoelectronic modulators, electronic countermeasure deception repeaters, and pulse radar and dual-mode ECM systems. As a traveling-wave-tube grid modulator, the unit provides 400-V output into a 100-ohm load in shunt



3. Beam bender. In a second type of EBS device, a traveling-wave structure deflects the electron beam, making it strike one of two diodes. This gives Class-B operation for good linear amplification. Amount of diode current depends on degree of beam overlap.

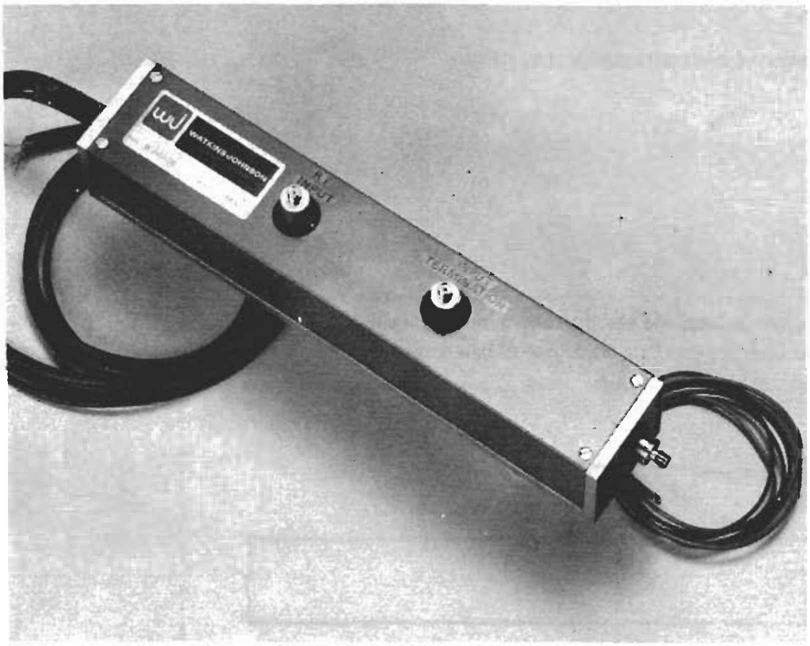


4. Shielded diode. An integral metal shield, formed by beam-lead-type process during diode manufacture, protects the diode's oxide and phosphosilica glass layers from the electron beam. This device was developed jointly by Watkins-Johnson and Signetics Corp.

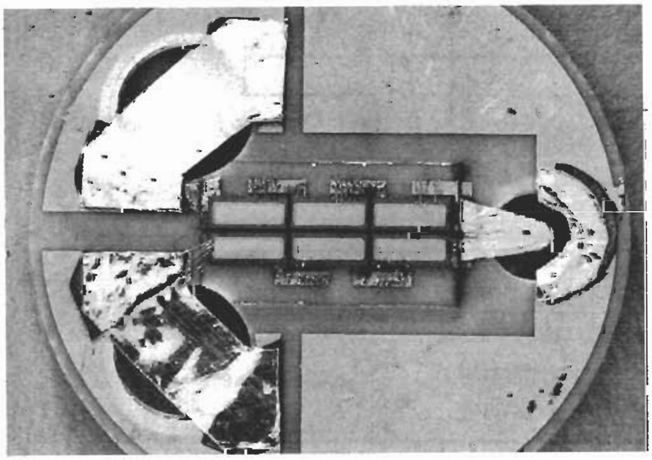
with 30-picofarad grid capacitance, with a total rise time plus delay of less than 12 ns. A modified version that can provide 850-V output is expected to be available within six to 12 months.

A high-current modulator also has been developed to produce 100 A into a 1-ohm load with a 2-ns rise time and up to 250 A at lower load impedances. Values of di/dt of 5 × 10^{10} A/s and peak powers of 12 kW have been achieved. Within the next 12 months, peak powers of 30 to 40 kW are expected, and ultimately 100 to 200 kW per device should be achievable.

A conduction-cooled cw low-pass rf amplifier, which uses a deflected beam, has a pulsed output power of 200 W from dc to 160 MHz. The cw or average-power capability of liquid- or forced-air-cooled versions is 50 W. A slightly different version of this device will give 25 V cw from dc to 310 MHz.



5. Ready to go. A completed EBS device is supplied in a configuration like a traveling-wave tube's. This unit, Watkins-Johnson's type 3650, is a deflected-beam video pulse amplifier with a gain of 25 decibels and a rise time of less than 1 nanosecond.



6. On target. Six diodes, arranged in two parallel sets of three and mounted on beryllium oxide heat sinks, comprise the target for a deflected-beam EBS device. A sheet beam from the electron gun illuminates each set of diodes alternately.

The linearity of a Class-B EBS is excellent: third-order intermodulation distortion for balanced two-signal operation is approximately 15 decibels down at saturation, and for 3-dB back-off from saturation, the third-order intermodulation signals are 25 dB below signal level. Total phase deviation from small signal to saturation is in the order of 3°. Recently, 500 W of pulsed rf power at 1,500 MHz with a bandwidth of 105 MHz was demonstrated. Performance improvements are expected in the next six to 12 months—over 100 W cw from dc to 300 MHz, and 50 W cw from 100 to 400 MHz and with 1,000 W pulsed rf power in the frequency range of 1 to 2 gigahertz with 5% to 10% bandwidth.

A deflected-beam video pulse amplifier will yield ±120 V output with 1-ns rise time into a 50-ohm load with approximately 25-dB gain. Operated as a cathode-ray-tube modulator, it will produce 80 V peak to peak to turn a CRT beam on or off. A bandwith of dc to 200 MHz, or the equivalent pulse rise time of 1.5 ns, has been measured with a 50-ohm load in shunt with a 5-pf capacitance (which is typical of the grid capacitance of some CRTs). Operated as a pulse amplifier, the same unit has produced 100 V output into a 50-ohm load at a 500-megabit data rate.

Thus, it is suited for a wide variety of linear video-amplifier requirements, and especially for rapid modulation of CRTs, electro-optic modulators, and high-power avalanche or Gunn devices. The output voltage will probably be increased within the year to ±250-V pulse at 10% maximum duty, or ±70 V cw into 50 ohms.

Where EBS devices will go to work

The primary impact of EBS power devices on the market in the next five years will most likely be in the areas of: high-voltage or high-current, very fast modulators; linear video amplifiers for fast pulse generation; modulators for data transmission systems, which will operate up to a 2-gigabit data rate; and linear rf amplifiers having a few hundred watts of cw output power or 1-to-2-kW pulsed output power for frequencies below 2 GHz.

Though in some cases the EBS device will replace an existing device, the greatest potential seems to lie in amplifiers beyond the capability of existing devices. As an example, a 400-W cw transistorized rf amplifier has been reported as operating at 0.96 to 1.18 GHz with a gain in the order of 20 dB. This amplifier, however, required more than 20 high-power transistors plus 28 hybrid power splitters and associated circuitry needed to combine all the transistors, whereas, in the near future, a single EBS device should give similar performance.

The major factor governing the share of applications captured by EBS devices will be price. The relative simplicity of the devices assures that the cost of large quantities will be reduced below $1,000, and in some cases well below $500, depending upon the requirements. The associated power supplies are expected to cost under $1,000 and in some cases, for low-duty application, under $500. Thus, complete laboratory-instrument amplifiers will be cost-competitive with existing medium-power TWT amplifiers and will complement them in the frequency range from dc to 2 GHz. ☐