Planar Doped Barrier Devices for Subharmonic Mixers

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Abstract

Mixers are a critical component of most millimeter wave and THz systems. Often, the front end mixer performance determines the overall system performance. At higher millimeter wave and THz frequencies, mixer performance can be limited by the lack of low cost solid state sources. A subharmonic mixer with a pumping frequency at half the signal frequency would reduce the source power requirements at these higher frequencies. Typical subharmonic mixers use back to back Schottky barrier diodes. The resulting structures are difficult to fabricate, and the performance can be degraded if the diodes are not matched and by parasitics associated with the various connections. One possible solution is to use an integrated Schottky barrier structure. Another possible solution is to use a planar doped barrier (PDB) as a single device subharmonic mixer. This paper will present an analysis of PDB subharmonic mixer performance.

I. Introduction

The PDB is a device that uses a symmetric doping structure to produce the anti-symmetric current vs. voltage characteristic required for subharmonic mixer operation. PDB structures can be modified to vary the barrier height, the capacitance per unit area and the space charge resistance. This allows a wide range of possible device structures. The device capacitance is approximately constant over a large RF voltage range. One potential disadvantage of the PDB is the "ideality factor". Since the structure is a series connection of two junctions the "ideality factor" is at least two. A variety of PDB structures have been studied to find the device characteristics and the performance as subharmonic mixers. Computer results show that the PDB has a conversion loss within 1.5 db of similar Schottky structures. This paper will present these results and a preliminary experimental characterization of the PDB structures. The organization of the paper is as follows. The next section contains a brief review of conventional Schottky barrier diode based subharmonic mixers. This information can form a basis of comparison for the PDB mixers. Section III contains a simplified description of PDB characteristics and a more complete numerical analysis of the current vs. voltage and capacitance vs. voltage characteristics of typical structures. This analysis points out the tradeoff's between the device structure and the resulting characteristics that are important for mixer performance. Section IV gives preliminary low frequency characterization results for the device structures discussed in section III. Section IV presents a computer analysis of subharmonic mixer parameters and performance for the structures of section III and IV. The paper is summarized in section V.

II. Conventional Subharmonic Mixers

Conventional Schottky barrier based subharmonic mixers have been the subject of a number of theoretical investigations and have be used in a variety of systems at frequencies at 100 GHz and above. Kerr[1] used the large signal time and frequency domain method developed by Held and Kerr[2] to analyze the performance of subharmonic mixers. This analysis described the performance of a dual Schottky barrier subharmonic mixer. The result predict conversion losses of 6 to 7 db and mixer noise temperatures of approximately 500 K for 100 GHz operation. The diodes and associated circuit were assumed to be matched in this study. The effects of unmatched diodes or circuits were studied by Hicks and Khan[3]. They found that small mismatch in the diode capacitances and lead inductance could greatly degrade the mixer performance. This study shows the importance of careful mounting structure design for these mixers.

Some of the best experimental results are described by Schneider and his coworkers[4-6]. These references describe subharmonic mixers operating between 65 and 100 GHz with conversion losses and noise figures in the 7 to 11 db range. The diodes used were individual notch-front GaAs mixer diodes. As the frequency increases the diodes become more difficult to match. One possible solution is an integrated structure. Marsh et.al.[7] describe a monolithic diode integrated circuit operating at 183 GHz. This mixer had a conversion loss of 5 db and a double sideband noise temperature of 600 K. These mixers use two waveguides and a quartz carrier to bring the signal and pump frequencies to the diodes and to extract the IF frequency. Some of this complexity can be overcome by using quasi-optical techniques to apply the signal and pump frequencies. A microwave frequency example of a quasi-optical mixer is described by Stephan and Itoh [8]. Another possible solution is to use a single planar doped barrier device to produce the required anti-symmetric current vs. voltage characteristic.

III. Planar Doped Barrier Devices

The planar doped barrier is an MBE growth technique that uses thin doping layers between more lightly doped regions to introduce or modify potential barriers in semiconductor structures. The technique was introduced by Malik et. al.[9]. A typical structure would have a p^+ doping spike between two intrinsic i layers with heavily doped n^+ contacts. The current vs. voltage characteristic of an asymmetric PDB is similar to a Schottky barrier characteristic. The PDB can be used as a Schottky barrier replacement with the additional advantage of barrier height control[10-11]. At 94 GHz a PDB single ended mixer had a noise figure of approximately 6 db and required only 280 μwatts of local oscillator power. If the p+ doping spike is placed in the middle of the structure, the current vs. voltage characteristic can be made anti-symmetric. Dixon and Malik[12] first showed subharmonic PDB operation at microwave frequencies. A millimeter wave

PDB subharmonic mixer with a 25 GHz signal bandwidth was described by Chen and Wong[13]. This device had a relatively large turn on voltage of 1.7 volts and a conversion loss of approximately 15 db. The purpose of this paper is to develop designs for PDB devices for operation at higher millimeter wave frequencies where low oscillator power is an important consideration.

An idealized planar doped barrier structure is shown in Fig. 1. The device designer has control of the material profile and dimensions. The device capacitance per unit area is determined by the width of the two i layers

$$C_{pdb} = \frac{\epsilon}{2l_i}, \tag{1}$$

where l_i is the width of one of the i regions in Fig. 1 and ϵ is the dielectric constant. Since the i layer width is controlled by the material structure and not by the bias conditions, the PDB capacitance is approximately constant with bias. The potential barrier height V_{pdb} is determined by the combination of the i layer width and the amount of charge in the p^+ doping spike,

$$V_{pdb} = \frac{qP_{spike}l_i}{4\epsilon} \tag{2}$$

where P_{spike} is the sheet density of charge in the doping spike and q is the electronic charge. A range of barrier heights are possible with proper choice of layer thickness and spike charge. The current vs. voltage characteristic of the PDB is

$$J_{pdb} = J_0 exp(\frac{qV}{2kT}) \tag{3}$$

where J_0 is a saturation current that depends on the barrier height. In a conventional Schottky barrier diode the "ideality factor" is a measure of the physics of the current transport across the barrier. It is near 1 for a good device at temperatures where tunneling current is small. The equivalent "ideality factor" for the PDB is two. The PDB is two junctions in series. The biased device acts as a voltage divider , with half of the applied bias appearing across the region to the right of the p^+ doping spike and the other half appearing to the left. This higher n factor is a potential limitation on the mixer performance of these devices. These approximations can be used to get an approximate device design. A more complete numerical analysis is needed to predict the device performance under large signal bias operation and to confirm these simple approximations.

A large signal computer program that solves Poissons' equation and the electron transport equation was developed to confirm the simple results given in equations 1 through 3. The capacitance vs. voltage characteristic of PDB structures with total i layer lengths of 500 and 1500 Å at 300 k is shown in Fig. 2. The capacitance is dependent on the i layer length and is approximately constant with bias voltage. The capacitance approximation given by equation 1 is correct except for a depletion of the contact regions. The increases the effective length and lowers the capacitance. The barrier height predicted by equation 2 depends on materials constants and the $P_{spike}l_i$ product. In fact the barrier height depends on the structure since there is charge redistribution near the edges of the i layers at the n^+ contacts. The barrier height of a PDB structure with a constant $P_{spike}l_i$ product and a variable i layer length is shown in Fig. 3. There is an approximately 20% variation in the barrier height as the i layer length is increased from 500 to 2000 Å.

The current vs. voltage characteristics of the PDB show the largest deviation from the simple theory. The current vs. voltage characteristic of two PDB structures with the same $P_{spike}l_i$ product and with total i layer thicknesses of 500 and 1500 Å are shown in Fig. 4. The difference in the current at low bias voltages is due to differences in the barrier height as shown in Fig. 3. The difference in the current at larger biases is due to space charge effects in the i layers of the device under high level injection conditions. The derivative of the electric field in the structure depends on the combination of the doping in the structure, and the density of the injected electrons. For low level injection conditions, the injected electron density is small, and the field slope is constant. As the density of injected electrons increases, the field slope is reduced and the change in voltage across the n^+ contacts required for a change in barrier height increases. The amount of injected charge in a long device is larger than in a short device, so the effect on the current vs. voltage characteristic is larger. The effect of this "space-charge resistance" is similar to series resistance in conventional mixer diodes and limits the minimum on resistance of the PDB device. The effect can be reduced by using shorter devices. A 500 Å long PDB has about the same depletion layer width and zero bias capacitance as a conventional epitaxial mixer diode with a doping of $2 \times 10^{17} cm^{-3}$.

With an i layer length of 500Å to reduce the space charge resistance, the P^+ doping can be varied to vary the barrier height and the turn on voltage. The current vs. voltage characteristics for three 500Å structures with P^+ sheet charges of $0.75, 1.0$ and $1.25 \times 10^{12} cm^{-12}$ are shown in Fig. 5. These curves show the wide range of barrier heights and turn on voltages possible with these structures and also show the reduced space charge resistance of the shorter structures. Structures with the material parameters of Fig. 5 were grown in GaAs using MBE. The experimental results are discussed in the next section.

IV. Planar Doped Barrier Device Characteristics

Initial work on the fabrication of PDB structures has begun to confirm the prediction of the last section. The devices are fabricated using the process sequence as follows:

Device Fabrication Sequence

1. GaAs MBE wafer growth with AlGaAs etch stops on GaAs substrate,
2. GeAuNi/Ti/Au ohmic contact deposition,
3. Au plated heat sinks,

4. Removal of substrate and etch stop layer,
5. Back side ohmic contact formation,
6. Mesa formation using chemical or RIBE etching,
7. Ohmic contact anneal.

We have started the initial characterization of three PDB structures. The 0.3 volt structure is shown in Fig. 6, the 0.5 volt structure in Fig. 7 and the 0.7 volt structure in Fig. 8. In these figures the current vs. voltage characteristics are for two mesa structures in series with contact to the top and unalloyed ohmic contacts. This initial characterization shows the basic device designs are correct. Work on complete device structures with the process sequence shown above is in progress.

V. Planar Doped Barrier Mixer Performance

We have started an initial characterization of the large signal mixer performance of PDB structures. This work used a large signal mixer analysis described by Maas[14]. This program is similar to the Held and Kerr program[2]. There are several tradeoffs in the performance in the performance of a PDB subharmonic mixer in comparison with a back to back Schottky barrier based mixer. The PDB has an n factor of at least two, in comparsion with an n factor of near one in a conventional diode. This higher n factor reduces the current modulation of the PDB. The effect of the n factor on the conversion loss of a subharmonic mixer is shown in Fig. 9. The figure shows the conversion loss of a subharmonic mixer vs. available local oscillator power for n factors between one and two and a constant barrier height of 0.7 volts. The higher n factor increases the amount of pump power required and slightly degrades the minimum conversion loss. The effect of the n factor can be overcome to some degree by control of the barrier height. Fig. 10 shows the conversion loss vs. local oscillator power for the range of barrier heights chosen for the experimental structures. The reduction of the barrier height reduces the required local oscillator power, even with the higher n factor. The lower barrier height slightly reduces the on to off ratio of the device and slightly degrades the conversion performance. For some applications, the Schottky mixer can be biased, which in effect lowers the barrier height. However, for high frequencies and for subharmonic operation, having two bias paths in the small waveguide structure would produce a complex structure than would not easily be matched. The unmatched structure would degrade the mixer performance. Although these are initial results, this data indicates that the PDB is a promising device for subharmonic applications.

Conclusions

This paper has given an overview of planar doped barrier devices for subharmonic mixer applications. These devices have a simple structure that will be useful for subharmonic operation. The simple design theory predicts the device capacitance and barrier height. The device current vs. voltage characteristic is strongly effected by space charge resistance. For best mixer operation the PDB should be as short as possible. Initial experimental results confirm the device designs. A large signal analysis was used to study PDB subharmonic mixer performance. The performance is a tradeoff between the advantages of lower pump power because of barrier height control and higher conversion loss due to a higher n factor. The devices under consideration had conversion losses within 1.5 db of a comparison Schotthy diode pair and required a quarter of the local oscillator power.

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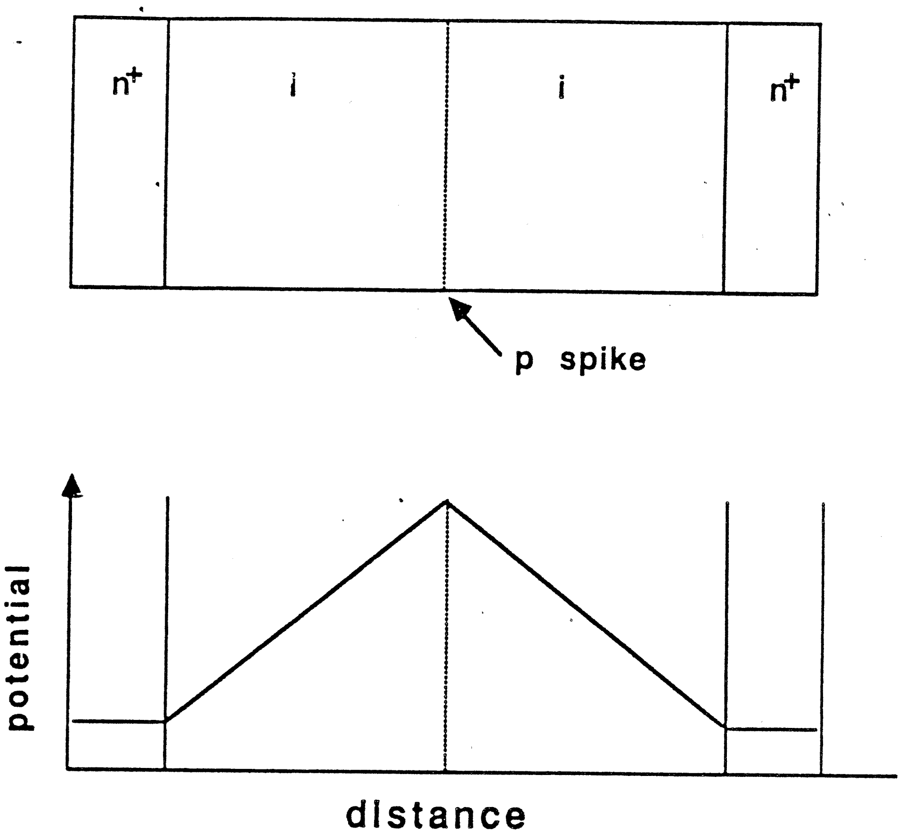
List of Figures

PLANAR DOPED BARRIER
(details)



Choice of

1) width
2) doping
3) material

Control

1) barrier height
2) resistance
3) capacitance

Figure 1

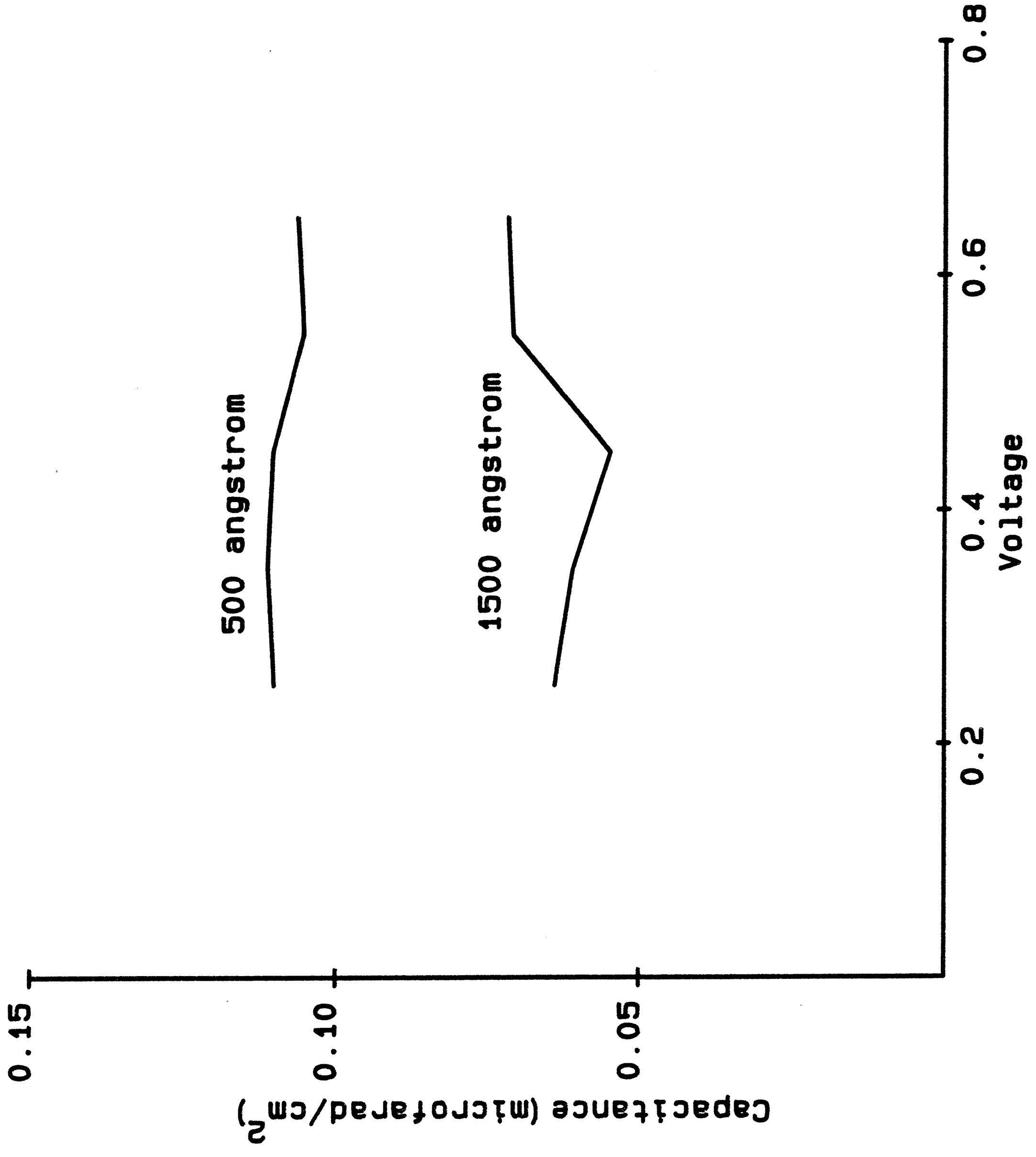
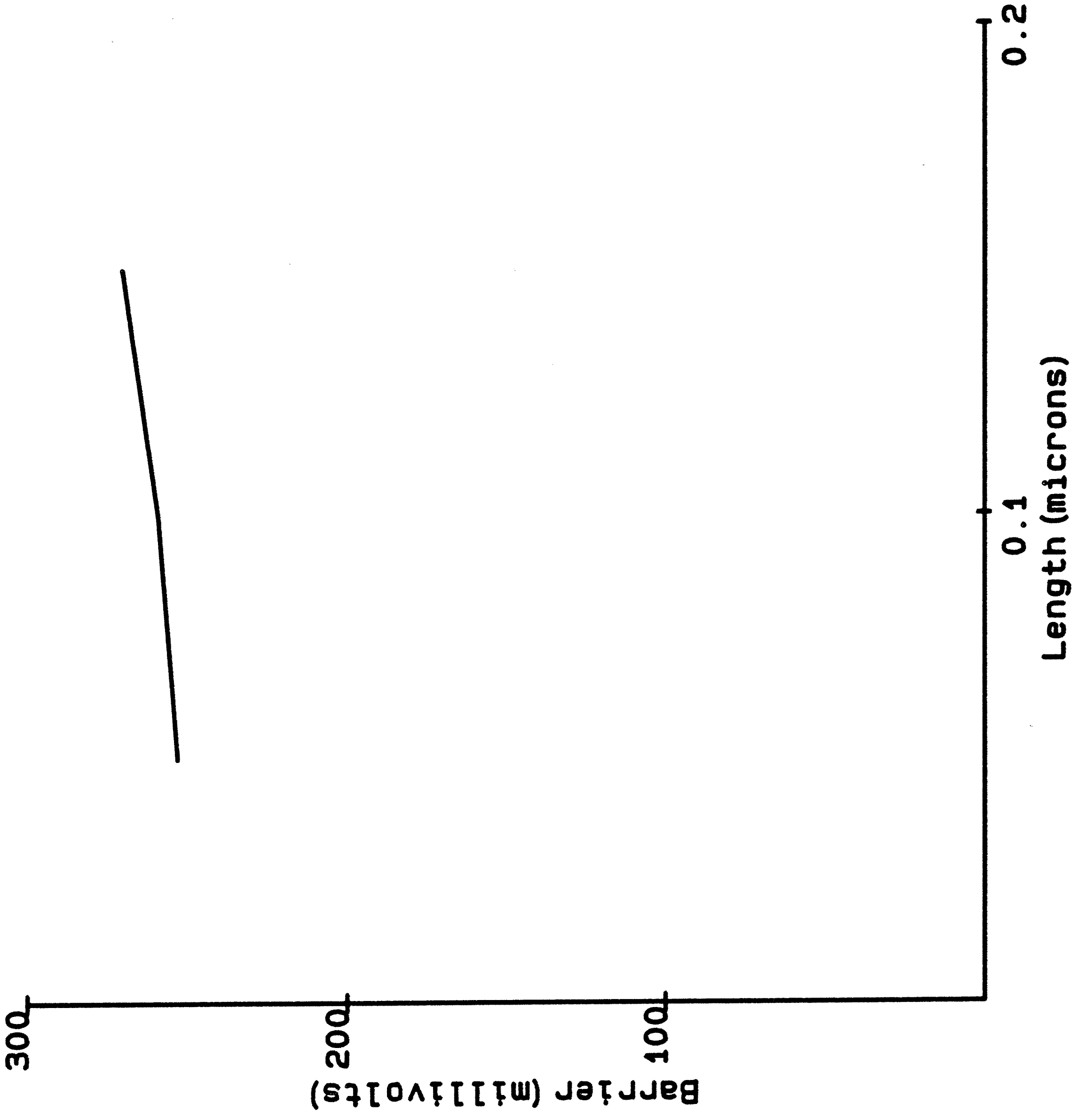

500 angstrom
1500 angstrom
0.2
0.4
0.6
0.8
Voltage
0.15
0.10
0.05
Capacitance (microfarad/cm^2)

Figure 2



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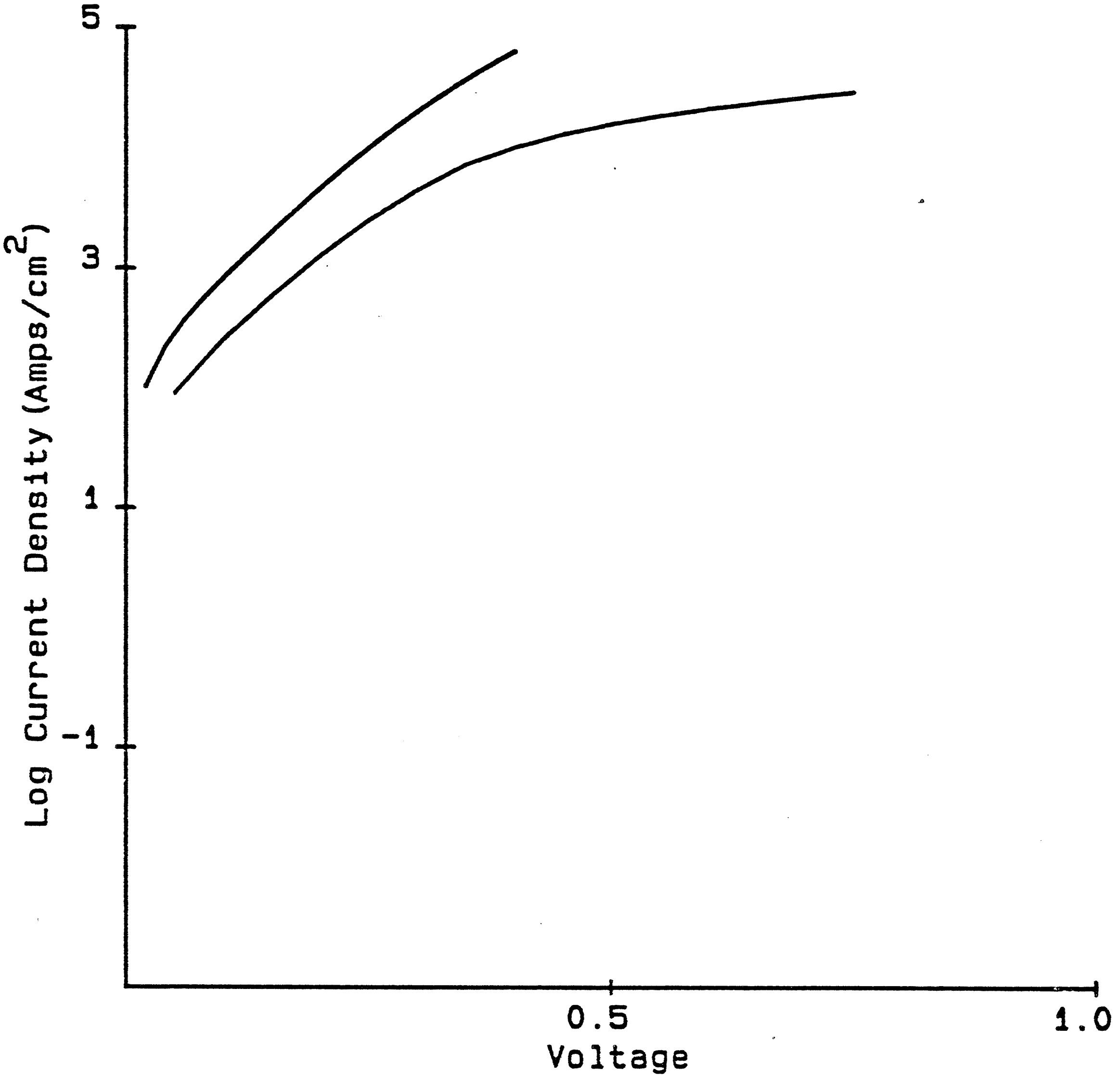

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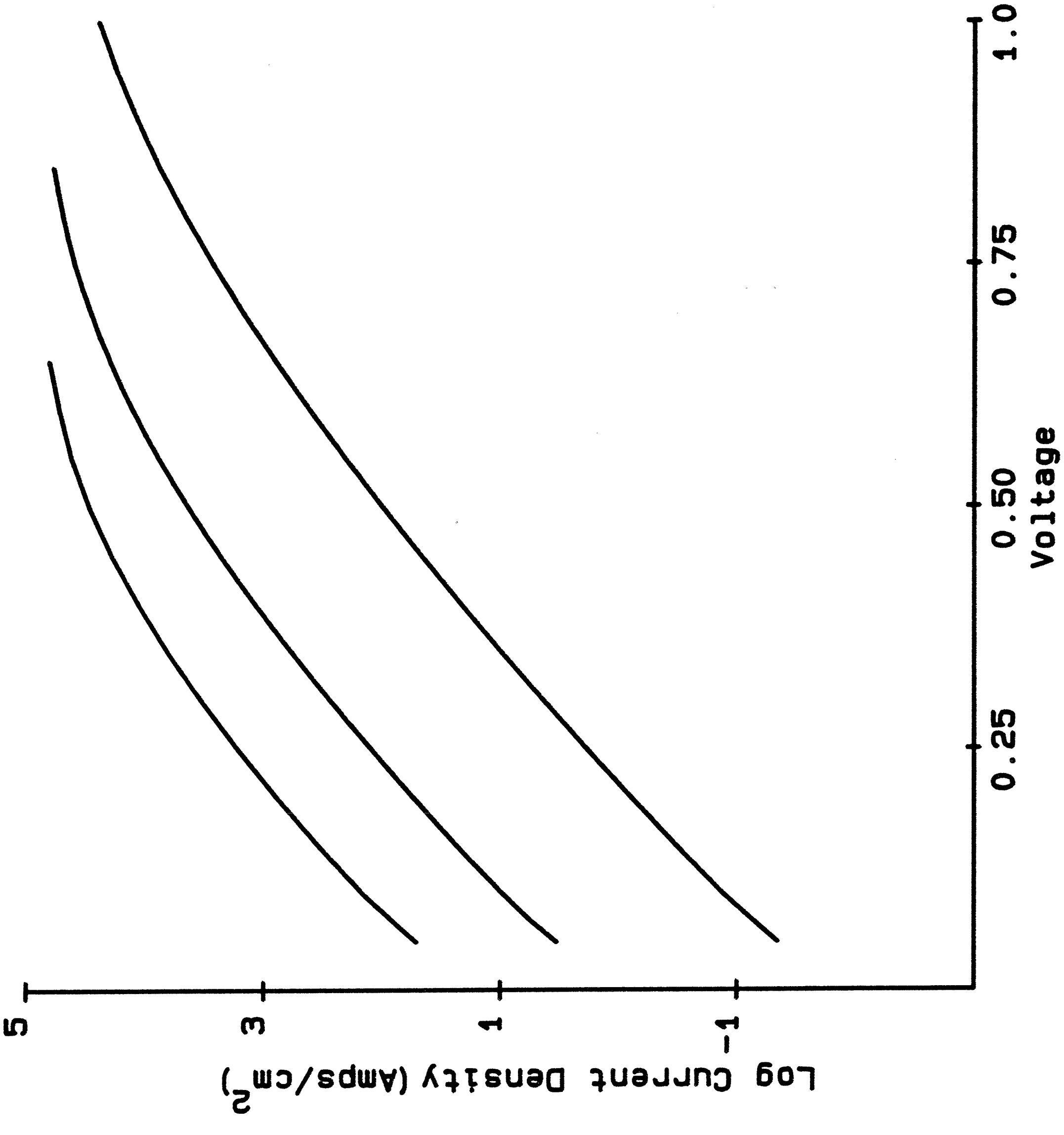

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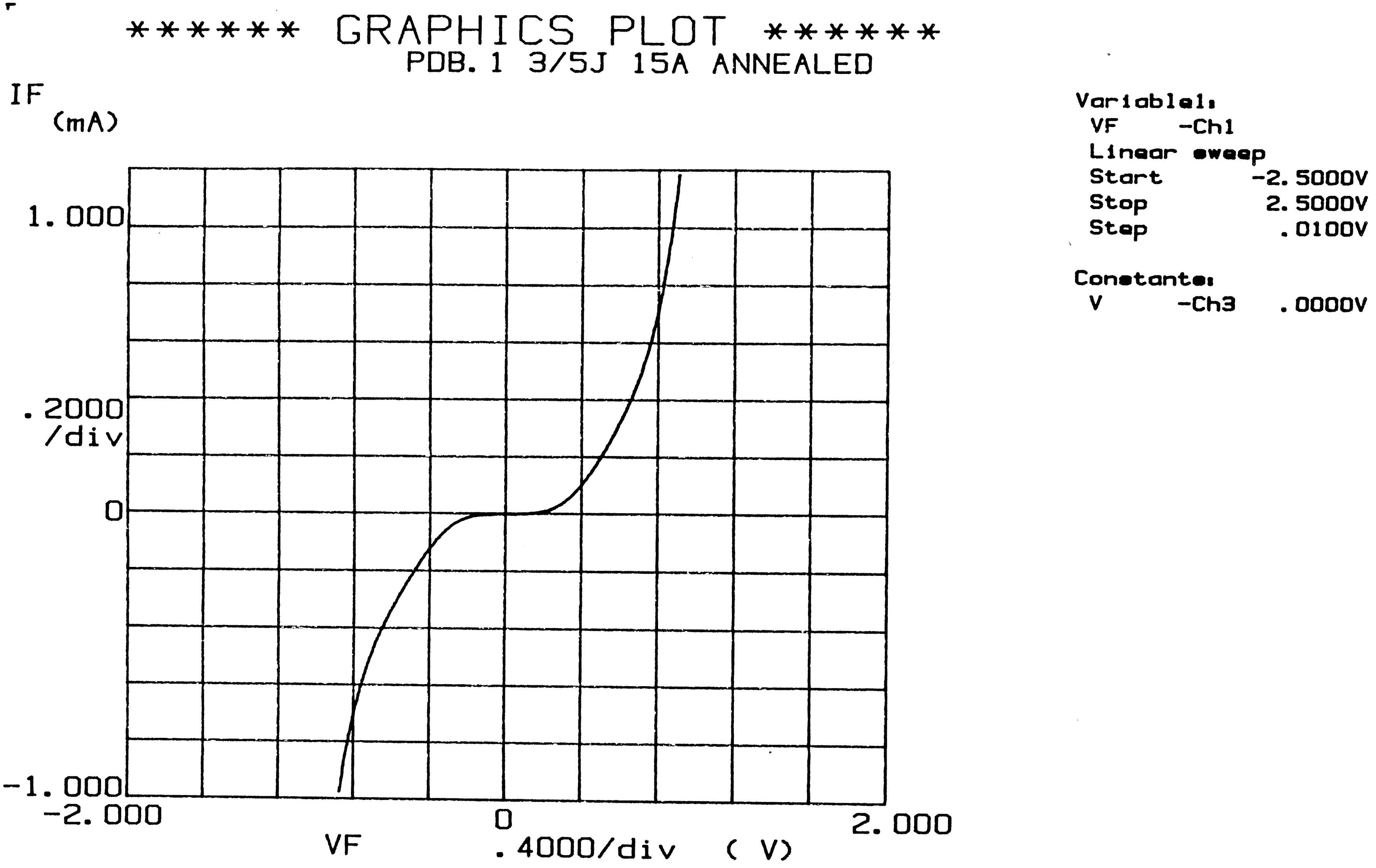

```
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 Linear sweep
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 Stop            2.5000V
 Step             .0100V

Constants:
 V       -Ch3     .0000V
```

Figure 6

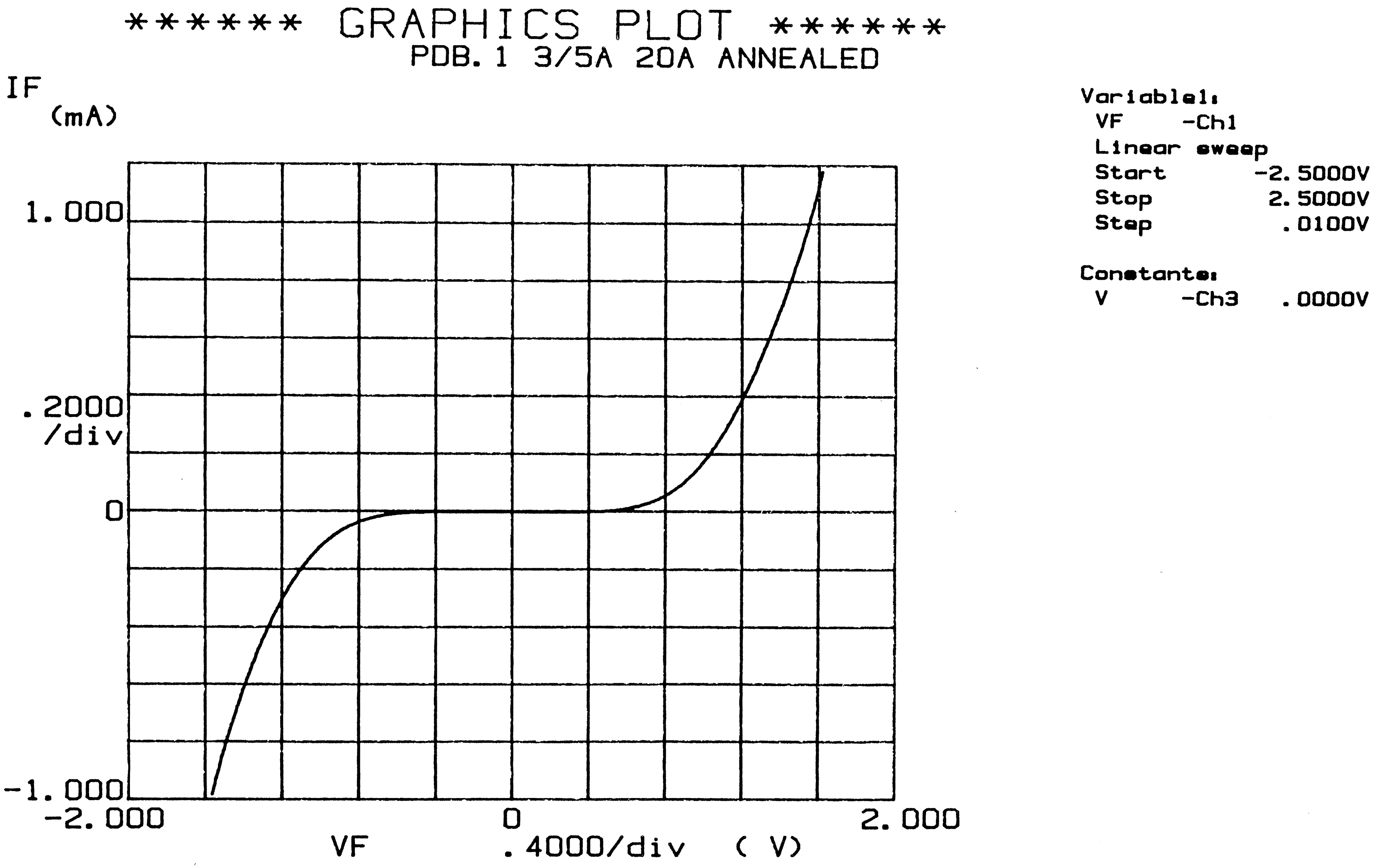
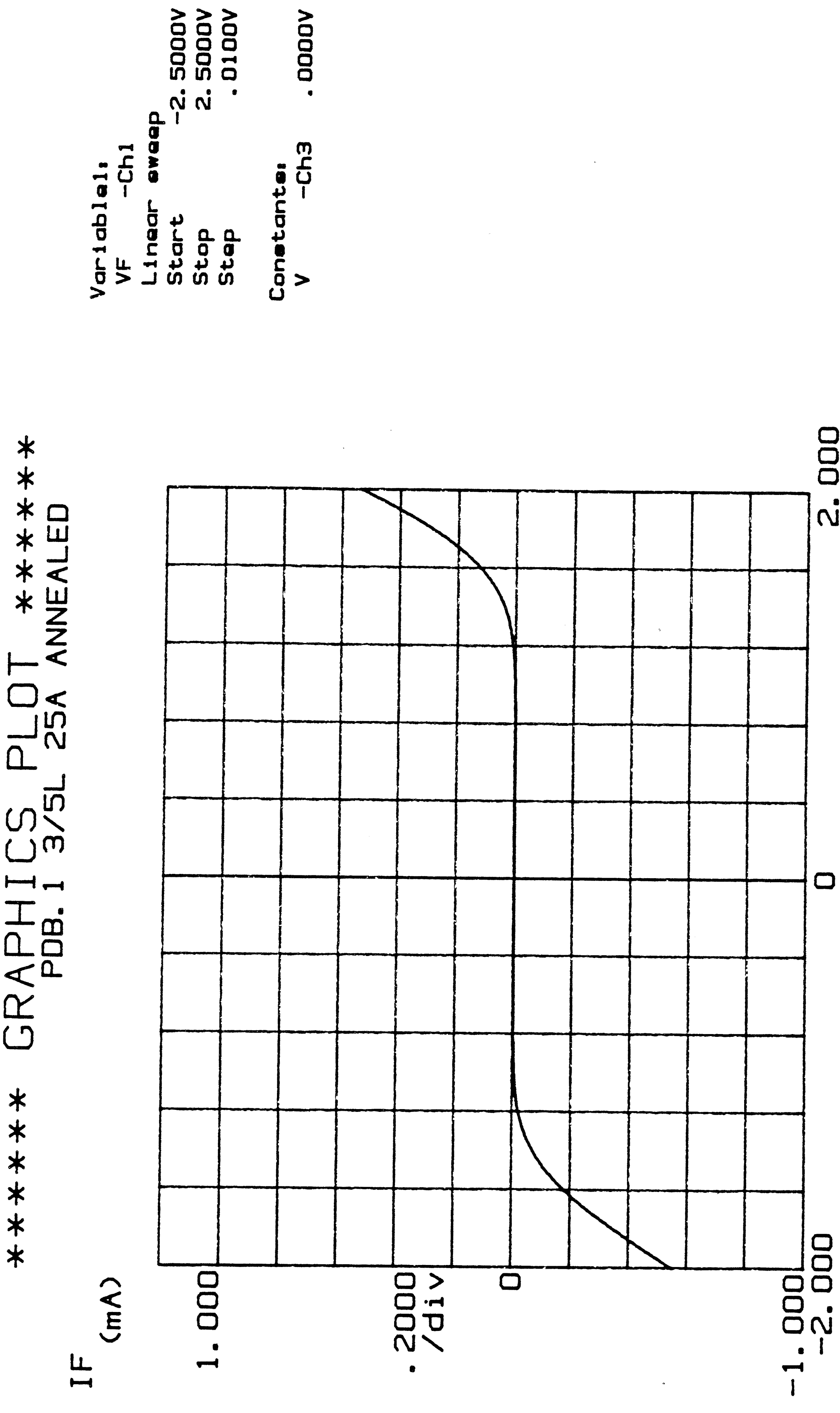

****** GRAPHICS PLOT ******
PDB. 1 3/5A 20A ANNEALED
IF (mA)
1. 000
. 2000 /div
0
-1. 000
-2. 000
0
2. 000
VF .4000/div (V)
Variable1:
VF -Ch1
Linear sweep
Start -2. 5000V
Stop 2. 5000V
Step . 0100V
Constants:
V -Ch3 . 0000V

Figure 7



Variable1:
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Linear sweep
Start -2.5000V
Stop 2.5000V
Step .0100V

Constants:
V -Ch3 .0000V

Figure 8

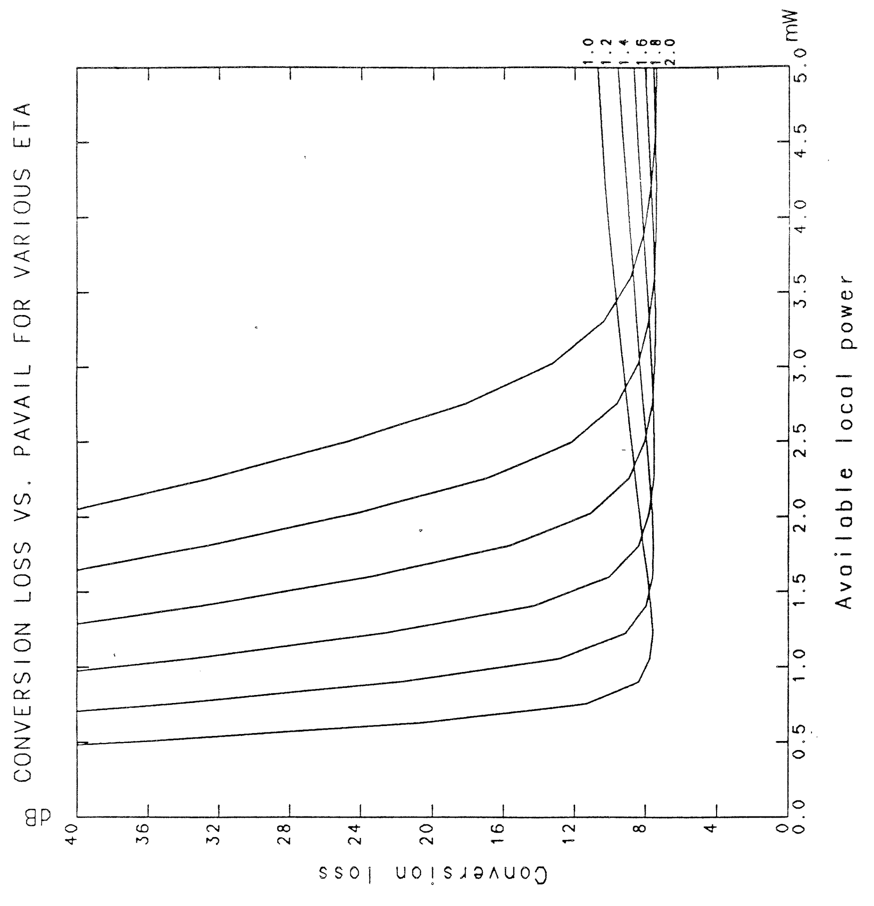

Figure 9

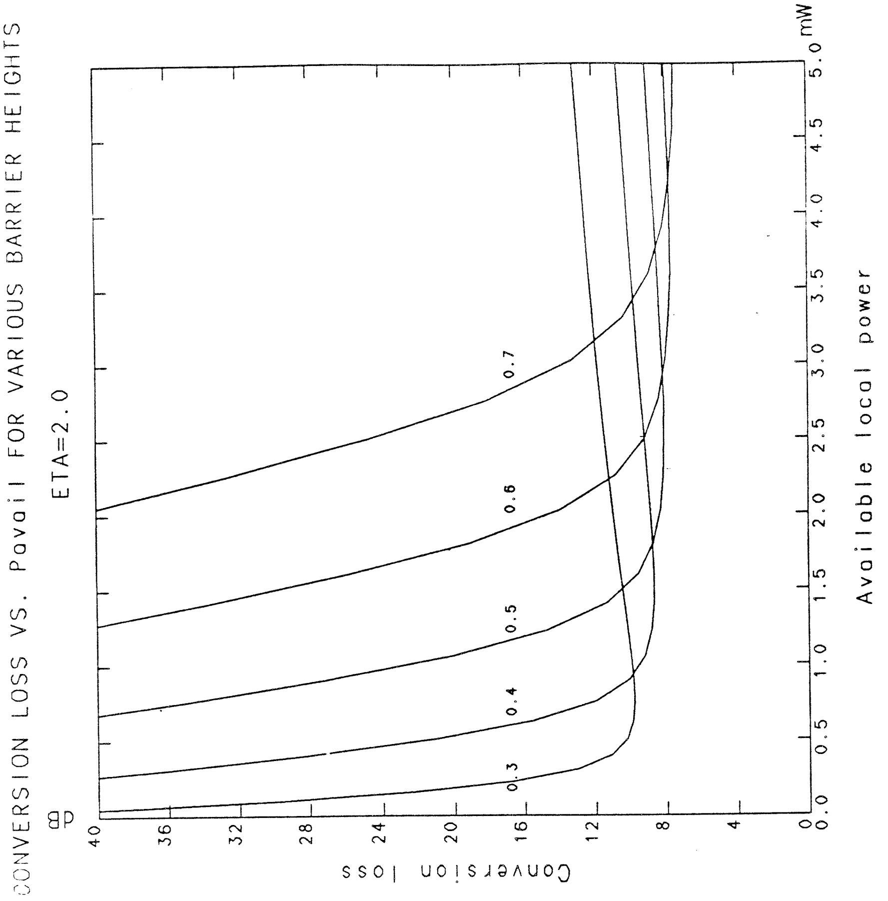

Figure 10