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**Invited**

# Silicon Permeable Base Transistors

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The silicon permeable base transistor (PBT) is considered to have potential for both high-frequency and high-speed applications. In this presentation, operating mechanisms of the PBT and theoretical predictions of high frequency performance based on two-dimensional numerical simulations are discussed. A fabrication procedure for etched-groove Si PBTs is described and rf results are presented. Best device results to date have been obtained from an etched-collector Si PBT which exhibits a small signal short-circuit unity-current-gain frequency, $f_t$, of 10 GHz, and a maximum frequency of oscillation, $f_{max}$, of 20 GHz. Device performance is presently limited by extrinsic capacitive and resistive elements. Reduction of these parasitic elements should yield an $f_{max}$ of approximately 50 GHz.

## I. Introduction

Recently, there has been considerable interest in modifying existing transistor structures and developing novel transistor geometries in order to extend the high frequency limit of three-terminal device operation. One approach is the vertical geometry unipolar device with ultra-short effective gate length such as the permeable base transistor (PBT)[1,2] and the static induction transistor (SIT)[3].

The unique feature of the PBT is the thin Schottky-contact base which is patterned into a submicrometer-period grating. Numerical simulations indicate that a PBT fabricated in Si with the structure shown in Fig. 1(a) should perform well as either a high frequency power[4] or logic device.[5,6] The fabrication of this structure requires Si overgrowth techniques to encapsulate a metal or metal-silicide grating. Overgrowth techniques, though successfully employed for GaAs[2], have not been demonstrated convincingly in Si, mainly because of its reactivity at the relatively high temperatures required for epitaxy.

Recent calculations[7] have shown that etched-groove PBT devices having the structures illustrated in Fig. 1(b) and 1 (c) have high-frequency performance virtually identical to the encapsulated-base PBT. These structures require the anisotropic etching of a Si n-layer to form the active region of the device. We have successfully employed reactive ion etching (RIE) to fabricate these types of Si PBTs; experimental results will be discussed below.

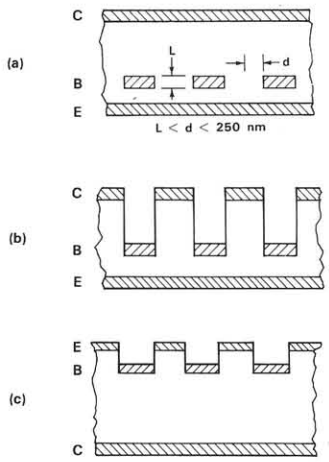


Figure 1. Three PBT configurations; a) encapsulated-base, b) etched-collector and c) etched-emitter. The base grating periodicity and metal thickness are 4d and L, respectively.

## II. Theory

Two-dimensional numerical simulations have been used to predict both dc characteristics and rf performance for the PBT structures of Fig. 1. The I-V characteristics illustrated in Fig. 2 are for the structure of Fig. 1(a) with grating periodicity

4d=320 nm, base thickness L=40 nm and semiconductor doping of 4 x $10^{16}$ $cm^{-3}$. Two distinct regions of operation can be observed. For low base-to-emitter biases, $V_{BE}$, the current density, $J_C$, is exponentially dependent on $V_{BE}$. This dependence is characteristic of barrier-limited current flow and yields device operation similar to a SIT. At high $V_{BE}$, $J_C$ exhibits a square-law dependence on $V_{BE}$ with a current saturation region similar to a conventional FET. Device operation can be made more "SIT-like" or "FET-like" by adjusting either the grating periodicity or the semiconductor doping. Our simulations[7] indicate that best high frequency performance is obtained for PBTs operated in the square-law region.

The two-dimensional nature of the depletion region around the base grating is of fundamental importance to the operation of the PBT. All sides of the base grating in contact with the semiconductor (see Fig. 1) contribute to the formation of the barrier to electron flow. The etched PBTs have lower transconductance, $g_m$, but also lower total capacitance, $C_T$, compared to the encapsulated PBT, because semiconductor material contacts only three sides of each base finger. However, the maximum of the ratio, $g_m/C_T$ (i.e., $f_t$), for all three intrinsic devices is nearly the same, as shown in Fig. 3. In addition to an $f_t$ close to 30 GHz, our simulations predict an $f_{max}$ for the intrinsic devices in the range of 90-100 GHz.[7]

## III. Fabrication

Although there have been no published reports of encapsulated-base Si PBTs, Japanese workers[8] have been experimenting with metal-silicides such as $CoSi_2$ and $NiSi_2$ which, in principle, can be overgrown by molecular beam epitaxy due to their close lattice matching with <111> oriented Si. We have found that $WSi_2$ submicrometer-period gratings can be successfully encapsulated in single-crystal Si using conventional CVD epitaxial techniques.[9]

For the etched-groove versions of the PBT, the fabrication sequence is summarized in Fig. 4. Initially, an n-layer is grown on an $n^+$ substrate. This is followed by a shallow As implant which is

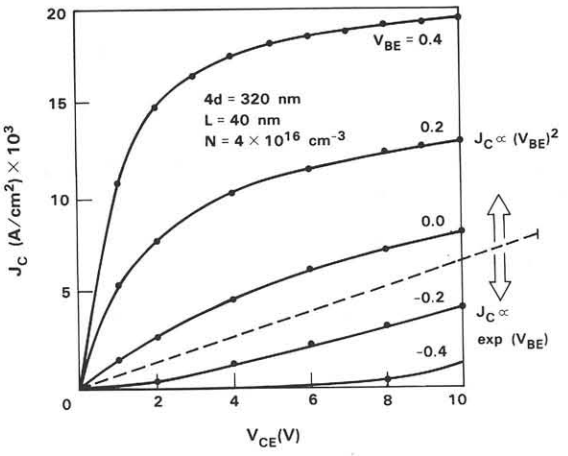


Figure 2. Calculated collector characteristics of an overgrown Si PBT. The dashed line indicates approximately the transition between the square-law and exponential dependence of $J_C$ on $V_{BE}$.

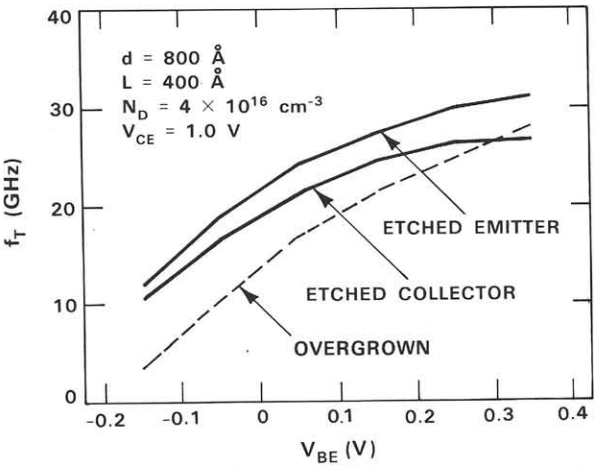


Figure 3. The unity short-circuit current-gain frequency $f_t$ as a function of $V_{BE}$ for the three devices of Fig. 1.

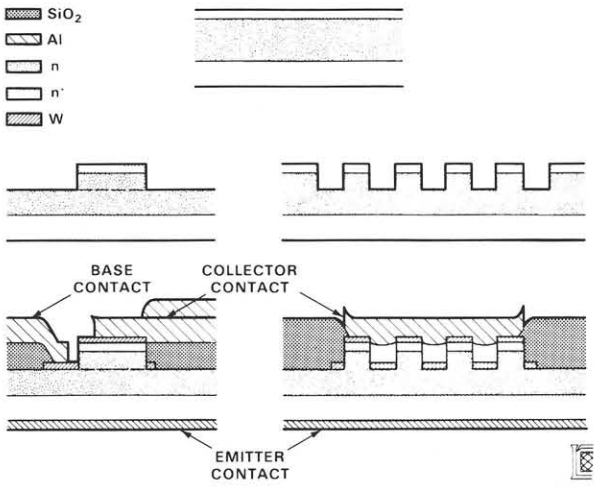


Figure 4. Fabrication sequence of the Si PBT. Cross-sectional views both parallel and perpendicular to the etched grooves are shown.

required for the top ohmic contact. The ability to control the doping precisely throughout the active region of the device is an important advantage of the etched-groove process compared to any encapsulated-base scheme. The critical step of the process is the fabrication of the straight-walled, etched-groove, submicrometer-period active region which is formed by using x-ray lithography and reactive ion etching, as previously described.[10,11] A W evaporation normal to the wafer surface produces, simultaneously, the collector and base regions of the device. The free-standing collector grating elements are connected by a sequence of Al evaporations at glancing angles which form an Al-W bridge. All of the principal features described above, including the submicrometer-period etched grating, the W base, the Al-W collector contact and the completed device are illustrated in the SEM sequence of Fig. 5. For the devices shown, grating periodicity is 320 nm, etched-groove depth is ~ 500 nm, W thickness is 60 nm and device active region is approximately 40 x 10 μm.

## IV. Device Results

Previously, we have reported on Si PBTs with an $f_{max}$ of 16 GHz.[12] Figure 6 shows the maximum available gain (MAG) and short-circuit current gain ($h_{21}$) as a function of frequency for the range 2-18 GHz calculated from measured S-parameters for our best device to date. This device was an etched-collector PBT with grating period 4d=240 nm, base thickness L=50 nm and semiconductor doping of $4x10^{16}cm^{-3}$. Extrapolated gains for $h_{21}$ and MAG to the unity-gain axis yield an $f_t$ of 10 GHz and an $f_{max}$ of 20 GHz. The MAG of 17 dB at 4 GHz is comparable to the best available Si bipolar devices.

Device parameters obtained from dc and S-parameter measurements indicate that $f_t$ is limited by parasitic capacitances such as those associated with the base and collector contact pads and the base finger shorting bar. If one considers the intrinsic device, consisting of the active region only, and the measured $g_m$, one obtains an $f_t$ of approximately 22 GHz or close to that predicted by the simulations.

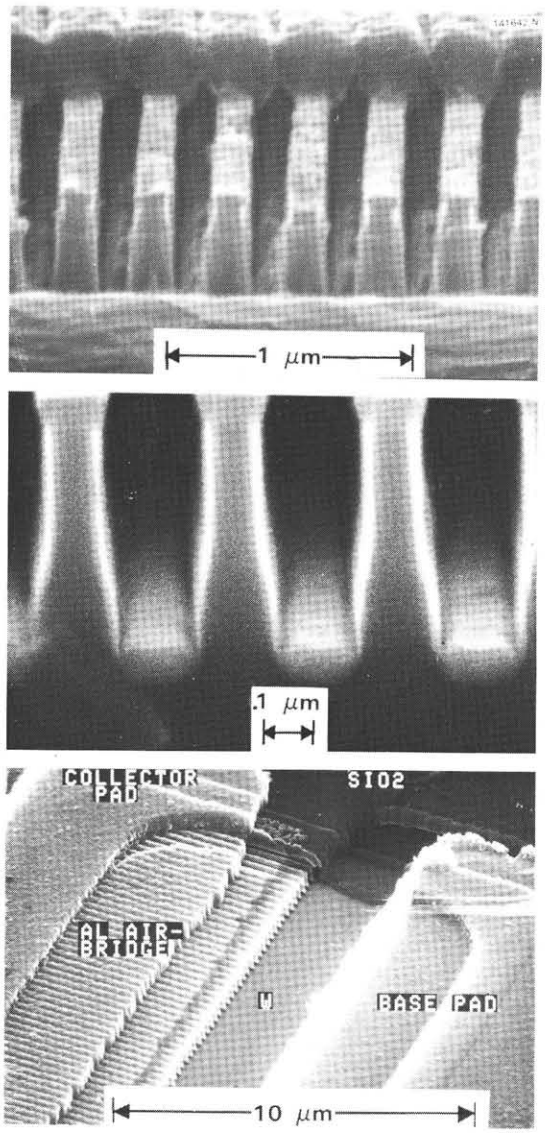


Figure 5. A series of SEM micrographs showing various features of an etched-collector PBT. (a) Al-W bridge on top of the collector grating, (b) 320 nm period grating with 60 nm thick W in the base region, (c) completed device.

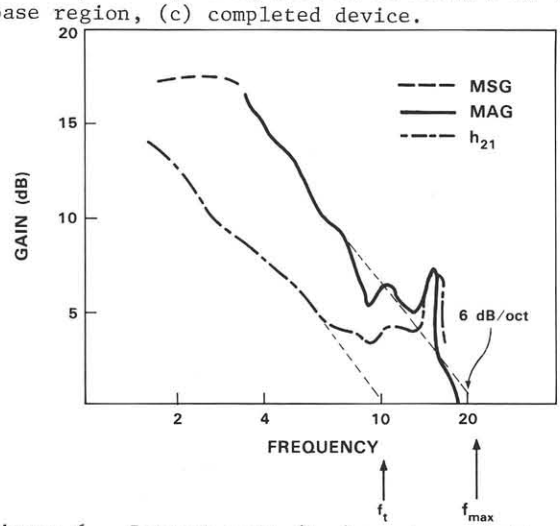


Figure 6. Current gain ($h_{21}$) maximum stable gain (MSG) and maximum available gain (MAG) as a function of frequency calculated from measured S-parameters for an etched-collector Si PBT.

$F_{max}$ is limited by contact resistance and output impedance in addition to $f_t$. The intrinsic device $f_{max}$ is 50 GHz which is a factor of two lower than theoretically predicted.

We believe the low output impedance for the etched-collector PBT is due to the presence of surface states on the exposed sidewalls. Surface states produce a barrier to current flow which is not independent of collector bias. This is in contrast to the current saturation and resultant high output impedance predicted by the simulations. For an etched-emitter PBT, surface states will lower $J_c$ and $g_m$ through an increase in emitter series resistance. Initial experiments indicate that the presence of a passivating dielectic such as $SiO_2$ or $Si_3N_4$ results in accumulation of this n-type surface which will eliminate this problem.

## V. Summary

The Si PBT has been shown theoretically and experimentally to be a device capable of operating at microwave frequencies. Although the initial results of an $f_t \approx 10$ GHz and an $f_{max} \approx 20$ GHz are quite respectable, we believe substantial improvement can be achieved. Efforts are currently directed toward reducing parasitic capacitances, lowering parasitic resistances associated with the base grating and the contacts, and scaling of both the grating periodicity and semiconductor doping to optimize performance. In addition, efforts are underway to fabricate simple integrated circuits.

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