tally confirmed. If η becomes larger, we can obtain much shorter pulse trains.

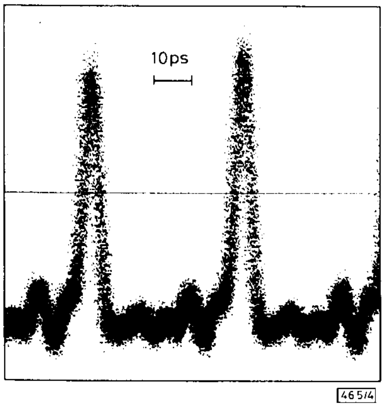

Fig. 4 *Experimentally generated pulse trains at 5 GHz repetition rate*

Conclusion: We have proposed a new method for generating optical short pulses by double gate operation using tandem connected EA modulators driven by sinusoidal voltage. We have shown that pulse trains with 2% duty cycle can be obtained theoretically. Pulse trains with 8% duty cycle at 5 GHz repetition rate were experimentally generated using a TEAM.

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OPTIMISATION OF BASE-LINK IN FULLY-IMPLANTED NPNs

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Indexing terms: Bipolar transistors, Ion implantation

It is demonstrated that the performance of washed-emitter NPNs can be significantly enhanced by using the washed-emitter-base (WEB) scheme. The characteristics of devices with cutoff frequencies from 15–27 GHz are discussed.

Introduction: A new base implantation flow for washed-emitter NPNs, the washed-emitter-base (WEB) scheme, is presented. With conventional methods of processing metal-contacted, implanted emitters the vertical and lateral downscaling is limited by current gain degradation due to, respectively, the transparency of shallow emitters to the injected minority-carrier current [1], and to the formation of a highly-doped sidewall diode. This parasitic diode usually prohibits scaling below 2 μm and to achieve a narrow base, very low emitter–base breakdown voltages and poor low-current characteristics must also be tolerated [2]. On the other hand, fully-implanted NPNs offer the advantage of low process complexity with high CMOS compatibility [2, 3]. The latter properties are preserved in the WEB processing scheme which involves an extra boron implantation but no extra mask steps. The base-link and intrinsic base are formed by separate boron implantations so that the doping profiles of the two regions are not directly coupled to each other. A sidewall diode can then be formed which allows downscaling of the emitter without modification of the current gain, Early voltages or breakdown voltages, as well as giving good low-voltage characteristics. Unlike conventional processing schemes, the major part of the intrinsic base is implanted *after* the emitter implantation directly into the emitter contact window. This, along with the high degree of scalability, also improves the reproducibility and parameter spread.

The fact that the heavily-doped sidewalls are eliminated in the WEB processing scheme, results in a very significant improvement of the emitter performance. Otherwise metal-contacted implanted emitters cannot be used to attain high-frequency performance comparable to that achieved with polysilicon emitter devices [4]. In this Letter the processing and characteristics of a 15 GHz WEB NPN are discussed. It is demonstrated that with either a pedestal collector implantation or a higher epitaxial doping, frequencies in the 20–30 GHz range are attained.

Processing: The conventional washed-emitter processing scheme is shown in Fig. 1*a*. The base is implanted before

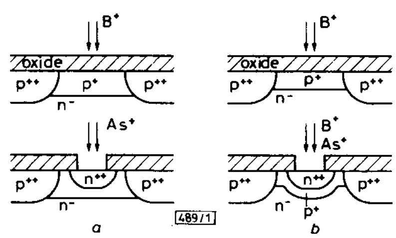

Fig. 1 *Schematic presentation of a conventional washed-emitter NPN implantation scheme and the WEB implantation scheme*

The oxide can be grown before or deposited after the first boron implantation
a Conventional implantation
b WEB implantation

emitter window etching and the resulting device, especially for shallow base implantations, has highly-doped sidewalls, the detrimental effects of which dominate the device characteristics for short emitter lengths. In the WEB processing scheme (Fig. 1*b*) described here, first a part of the base is implanted to provide base link-up. The emitter window is then etched and implanted with 40 keV arsenic, thus amorphisising the surface for the subsequent intrinsic base implantation. After completing all implantations, the dopants are activated by a 30 min thermal anneal at 950°C, and contacted by sputtering Al/1% Si. With a 20 keV intrinsic base implantation, the scalability of the emitter has proven to be very high if the base-link implantation is shallow. The sheet resistance of the base-link can then be varied from 800 to 2500 Ω/□ without effecting the scalability of the emitters, indicating that the intrinsic base implantation itself is primarily responsible for the electrical characteristics of the emitter sidewalls. In all cases the base-link doping contributes less than 25% to the total intrinsic base doping, which minimises the susceptibility to base doping removal during plasma etching of the emitter contact window. The spread in current gain over the wafer is 100 ± 10.

Device characteristics: The following characteristics are given for devices with an antimony buried layer, a 1 μm epitaxial layer (normal doping $10^{16}/cm^3$), and implanted p^+ isolation and collector plug. The metal pitch is $3\,\mu m$. The DC characteristics for two NPNs with different emitter area A_E are compared in Fig. 2, displaying both the very good scalability of the DC parameters and ideal low voltage characteristics. Any sidewall suppression of the f_T is very small as demonstrated in Fig. 3, which features a maximum f_T of 15 GHz. A summary

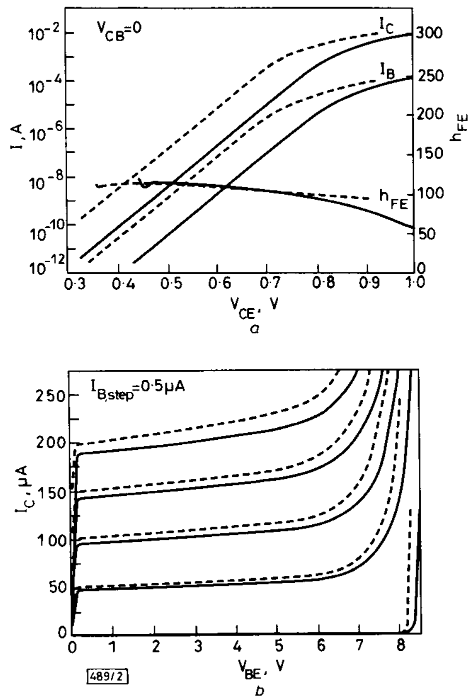

Fig. 2 *Gummel plots and output characteristics of two 15 GHz WEB NPNs, with A_E = 20 × 1 µm² or 20 × 40 µm²*

a Gummel plots
b Output characteristics
——— $A_E = 20 \times 1\,\mu m^2$
– – – – $A_E = 20 \times 40\,\mu m^2$

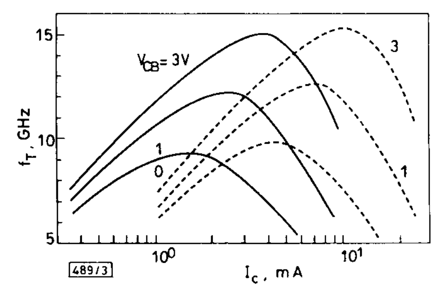

Fig. 3 *Cutoff frequency against collector current for two 15 GHz WEB NPNs, with A_E = 20 × 1 µm² or 20 × 4 µm²*

——— $A_E = 20 \times 1\,\mu m^2$
– – – – $A_E = 20 \times 40\,\mu m^2$

of the device parameters is given in Table 1, which shows that the high frequency response has not been achieved at the expense of either high base resistance or low breakdown voltages.

Devices with a selfaligned pedestal collector were fabricated by also implanting phosphorus at 360 keV in the emitter contact window. With an effective collector doping of $1{\cdot}5 \times 10^{13}/cm^2$ at the base–collector junction, an increased intrinsic base doping is necessary for maintaining an h_{FE} around 100, but the emitter scalability and good low voltage characteristics are preserved. In this way a 23 GHz device was fabricated. Devices with no pedestal collector but instead a highly doped epitaxial layer ($8 \times 10^{16}/cm^3$) were also produced and an f_T of 27 GHz was obtained. Other parameters are compared in Table 2. The total intrinsic base doping has not been reduced to achieve the higher f_Ts, but the high collector doping nevertheless makes the Early voltages and BV_{CEO} low.

Table 1 DEVICE PARAMETERS OF 15 GHz WEB NPN, $A_E = 20 \times 1\,\mu m^2$

HFE	90
Forward Early voltage [V]	45
BVEB [V]	4·0
BVCEO [V]	8·5
BVCBO [V]	18·5
Intrinsic base sheet resistance [Ω/□]	9500
Base-link sheet resistance [Ω/□]	1060
RE [Ω]	3
RB [Ω]	60
C_{eb} [fF]	100
C_{bc} [fF]	60
Peak f_T, $V_{CB} = 3$ V [GHz]	15

Table 2 DEVICE PARAMETERS OF TWO WEB IPNs ($A_E = 20 \times 1\,\mu m^2$)

	(*a*)	(*b*)
HFE	70	110
Forward Early voltage [V]	14	6·5
BVCEO	3·4	3·5
Intrinsic base sheet resistance [Ω/□]	9100	14000
C_{eb}	105	86
C_{bc}	70	120
Peak f_T, $V_{CB} = 3$ V [GHz]	23	27

a With pedestal collector
b With high epitaxial doping

Conclusion: Owing to the improved emitter-sidewall characteristics provided by the base-link of the WEB structure, high performance NPNs with washed emitters can be fabricated in a straightforward and reproducible manner. The 15 GHz devices have good overall characteristics. In the 20–30 GHz range further device optimisation is necessary to improve the DC characteristics.

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