The measurement results are shown in Figs. 4 and 5, respectively. From these results it can be concluded that the extra DC photocurrent hardly affects the transfer function (Fig. 4) and the signal spectrum around a frequency of 36 kHz (Fig. 5).

Fig. 5 Measured output spectrum
(i) without DC photocurrent
(ii) with DC photocurrent

Finally, the measured total power consumption of the circuit amounted to 24 μ W.

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FAST CALCULATION METHOD FOR MULTICOMPONENT WIGNER-VILLE DISTRIBUTION

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Indexing terms: Signal processing, Digital signal processing, Mathematical techniques

Owing to its bilinear nature, calculation of the Wigner-Ville distribution (WVD) produces crossterms between independent frequency components. Usually an averaging technique is adopted to smooth out these terms, the calculation time being proportional to the averaging times. Using the linear nature of averaging and Fourier transform (FT), this technique is improved resulting in a range saving of calculation time.

Crossterms: A typical two-component analytical signal is

$$x(n) = e^{j(n\omega_1 + \phi_1)} + e^{j(n\omega_2 + \phi_2)} \quad (1)$$

The discrete Wigner-Ville distribution (DWVD) using a rectangular window of length $2L + 1$ is [1]

$$W_x(n, \omega) = \text{sind}_L(\omega - \omega_1) + \text{sind}_L(\omega - \omega_2) + 2 \cos[(\omega_1 - \omega_2)n + \phi_1 - \phi_2] \times \text{sind}_L\left(\omega - \frac{\omega_1 + \omega_2}{2}\right) \quad (2)$$

where $\text{sind}_L(x) = \sin[(2L + 1)x]/\sin x$.

We see that there is a crossterm between ω_1 and ω_2 , of frequency $(\omega_1 + \omega_2)/2$ and modulated with frequency differ-

ence signal. When ω_1 and ω_2 are far apart, it is simply an unnecessary interference and is often easily smoothed out by averaging spectra in a period of

$$S = \frac{2\pi}{\omega_1 - \omega_2} \quad (3)$$

When the two components are close, its existence substantially reduces the spectral resolution; the averaging period or the number of DFTs increases in inverse proportion to $\omega_1 - \omega_2$. Therefore a direct averaging technique is practically prohibited of distinguishing close components and the WVD estimator cannot demonstrate its advantage of high frequency resolution.

Reducing the averaging computation: Let us examine WVD formulation from the end. The finite lengthened DWVD is

$$W_x(n, \omega) = \sum_{m=-L}^L x(n+m)x^*(n-m)e^{-j2m\omega} \quad (4)$$

or the DFT of kernel $K_x(m) = x(n+m)x^*(n-m)$. Because both the DFT and average are linear transformations, their order is exchangeable. We may average the kernel on n first, then only one DFT is needed to produce the averaged spectrum. The computation time of the set kernel increases with S , but it is far less than calculating an FFT [2] S times before averaging the spectra.

Example: The test analytical signal consists of two components $\omega_1 = 2\pi/8$ and $\omega_2 = 2\pi(1.04/8)$ computed on an IBM 286 computer. To obtain a 512 point DWVD spectrum, the old technique takes 49 min, and the improved takes only 107 s.

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GSMBE GROWN (GaIn)P/GaAs HETEROJUNCTION BIPOLAR TRANSISTORS EXHIBITING CURRENT GAINS UP TO 590

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Indexing terms: Bipolar devices, Transistors, Semiconductor devices and materials

The first lattice-matched $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}/\text{GaAs}$ heterojunction bipolar transistor grown by gas-source molecular beam epitaxy is reported. Small signal current gains exceeding 590 and small offset voltages (~ 120 mV) were obtained. These results demonstrate that (GaIn)P is a good alternative to the (AlGa)As in GaAs-based devices.

Introduction: Heterojunction bipolar transistors (HBT) have been shown to be very promising in the area of microwave applications. These devices have been made and studied in several material systems, but most extensively in the GaAlAs/GaAs system. Recently, there has been interest in the $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}/\text{GaAs}$ material system because of its large valence band discontinuity ($\Delta E_v = 0.24$ - 0.3 eV [1-4], 0.4 - 0.43 eV [5, 6]) and smaller conduction band discontinuity ($\Delta E_c = 0.19$ - 0.22 eV [1-4], 0.03 - 0.06 eV [5, 6]) compared with the band discontinuities of the AlGaAs/GaAs material system for the same bandgap energy difference. The $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}/\text{GaAs}$ heterostructure, where most of the

energy gap discontinuity occurs in the valence band, is very suitable for obtaining high electron injection efficiency from the emitter to the base and thus a high heterojunction bipolar transistor (HBT) current gain [7]. Since the introduction of $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}/\text{GaAs}$ HBTs by Kroemer [8], several devices have been grown and fabricated [5, 7, 9–12]. Their devices were grown by solid-source molecular beam epitaxy (MBE) [9, 11], metal organic chemical vapour deposition (MOCVD) [5, 10, 12], or chemical beam epitaxy (CBE) [7]. We report the results of the first $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}/\text{GaAs}$ HBT grown by gas source molecular beam epitaxy (GSMBE). A small signal current gain exceeding 590 and a small offset voltage ($\sim 120\text{ mV}$) in common-emitter current-voltage characteristics were achieved. To our knowledge, the current gain achieved is the highest reported value in $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}/\text{GaAs}$ HBTs to date.

Material growth: Our $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}/\text{GaAs}$ HBT structure was grown as follows: first, a $5000\text{ \AA}$ GaAs n^+ ($2 \times 10^{18}\text{ cm}^{-3}$, Si doped) buffer layer was grown on a $(100)\text{ n}^+\text{-GaAs}$ substrate, followed by a $5000\text{ \AA}$ GaAs n^- ($5 \times 10^{16}\text{ cm}^{-3}$, Si doped) collector layer. The base was a $1000\text{ \AA}$ GaAs p^+ ($2 \times 10^{18}\text{ cm}^{-3}$, Be doped) layer. A $500\text{ \AA}$ GaAs spacer was then grown between the p^+ base and the $2500\text{ \AA}$ n^- ($1 \times 10^{17}\text{ cm}^{-3}$, Si doped) $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ emitter. Finally, a $2000\text{ \AA}$ n^+ ($5 \times 10^{18}\text{ cm}^{-3}$, Si doped) emitter cap layer was grown. The substrate temperature was held at 490°C when the $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$ emitter was grown. The schematic diagram of the HBT layer structure is shown in Fig. 1.

n^+ GaAs emitter cap	$5 \times 10^{18}\text{ cm}^{-3}$	Si doped $2000\text{ \AA}$
InGaP emitter	$1 \times 10^{17}\text{ cm}^{-3}$	Si doped $3500\text{ \AA}$
GaAs spacer	undoped	$500\text{ \AA}$
p^+ GaAs base	$2 \times 10^{18}\text{ cm}^{-3}$	Be doped $1000\text{ \AA}$
n^- GaAs collector	$5 \times 10^{16}\text{ cm}^{-3}$	Si doped $5000\text{ \AA}$
n^+ GaAs buffer	$2 \times 10^{18}\text{ cm}^{-3}$	Si doped $5000\text{ \AA}$
n^+ GaAs substrate		

Fig. 1 Schematic diagram of GaInP/GaAs heterostructure

Device fabrication: Large contact devices were realised using a simple double mesa technology. First a $1000\text{ \AA}$ thick Au/Ge/Ni was deposited and lifted off on the cap layer for the emitter ohmic contacts, which were circular dots $100\text{ }\mu\text{m}$ in diameter. The emitter mesa formed by selective wet etching of the emitter cap layer and emitter layer with the solutions of $\text{H}_2\text{O}_2:\text{NH}_4\text{OH}$ ($\text{pH} = 8.4$) and $1\text{HCl}:\text{H}_2\text{O}$ solution, respectively. The undoped spacer was etched by

Fig. 2 Common-emitter current-voltage characteristics of GaInP/GaAs heterojunction bipolar transistor

$\text{H}_2\text{SO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$ to expose the base for Au-Zn evaporation to form good ohmic contacts. Finally, the active devices were isolated by mesa etching in a $\text{H}_3\text{PO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$ solution. The 'back' of each sample was evaporated with Au/Ge/Ni for collector electrical contact.

Results and discussions: Typical common-emitter current-voltage (I - V) characteristics of a fabricated HBT are shown in Fig. 2. Note that the offset voltage is small ($\sim 0.12\text{ eV}$) even though no grading was used. This offset voltage agreed with that of Alexandre *et al.* [7] where the HBTs were grown by CBE. This value of offset voltage seems to imply the conduction band discontinuity ΔE_C should be around or less than 120 meV . This is consistent with the recent result ($\Delta E_C = 108\text{ meV}$) of Haase *et al.* [13], who have determined the value of ΔE_C by measuring the internal photoemission of GaAs-GaInP p - i - N heterojunction photodiodes grown by the same growth technique (GSMBE). The small signal current gain h_{fe} against collector current I_C is plotted in Fig. 3. As can be seen clearly, a very high current gain (593) was achieved. The above results indicate that $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}/\text{GaAs}$ is indeed a very good material system for the HBT structure because it can keep the current gain high and the turn-on voltage low without any grading.

Fig. 4 shows the plots of the collector current I_C and base current I_B as a function of emitter-base voltage V_{BE} . The

Fig. 3 Current gain against collector current of GaInP heterojunction bipolar transistors

Fig. 4 Collector current and base current against emitter-base voltage of GaInP/GaAs heterojunction bipolar transistors
 n values are ideality factors

ideality factor n of I_C was 1.00 and that for I_B was 1.89. This high value of ideality factor (1.89) for base current implies that there was still large surface recombination current in the extrinsic base region. We believe that further increase of current gain could be obtained by some surface protection techniques [14, 15].

Conclusions: This Letter is the first demonstration of a $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}/\text{GaAs}$ HBT grown by gas source molecular beam epitaxy (GSMBE) with a high current gain (593) and a small offset voltage (120 mV). The performance of the device indicates that GSMBE is a very good technique for growing InGaP/GaAs HBTs. This InGaP/GaAs structure has the advantages of ease of growth (no grading) and fabrication (wet selective etching), and good uniformity. Our results suggest that the $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}/\text{GaAs}$ system could be a good alternative for the $\text{AlGaAs}/\text{GaAs}$ based HBTs as predicted by Kroemer [8].

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ALL-OPTICAL PRESSURE SENSOR WITH TEMPERATURE COMPENSATION ON RESONANT PECVD SILICON NITRIDE MICROSTRUCTURES

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Indexing terms: Optical sensors, Resonators, Sensitivity

A novel sensor is presented incorporating easy separation of pressure and temperature sensitivity, both of which affect the frequency of a resonating bridge. With PECVD silicon nitride as bridge material, pressure sensitivities up to 86% per bar were achieved.

Introduction: There has been considerable interest in sensors which give direct digital or frequency-coded output signals [1-3]. A well known approach is a silicon micromechanical bridge pressure sensor, especially an all-optical sensor based on photothermal excitation [4-6]. External environmental parameters such as pressure and temperature can affect the mechanical state of the resonator and change the frequency at which resonance occurs.

A problem with these sensors is the cross-sensitivity to various parameters, especially temperature. The application of plasma-enhanced chemical vapour-deposited (PECVD) silicon nitride as a bridge material has been investigated, which allows the production of bridge material with high sensitivity. The mechanical properties can be controlled by means of the processing conditions, for example low tensile stress. To distinguish between the sensitivity to pressure and to temperature, we position a second bridge near to the first which is only temperature-sensitive (Fig. 1). This method allows temperature compensation of the measured pressure signal. Detection is performed by means of an interferometric setup: silicon planar technology may offer the possibility of future monolithic integration of such an interferometer with the sensor structure.

Fig. 1 Microresonator bridge sensor

Device construction: 2.8 μm PECVD silicon nitride was deposited on double-sided polished 320 μm thick silicon (100) wafers. The bridges were defined by photolithography and had dimensions of $577 \times 6 \times 2.8 \mu\text{m}^3$. The pit has dimensions of $1 \times 2 \text{ mm}^2$ and is 30 μm deep. The wafer processing is chosen to etch a 30 μm thick diaphragm. All bridges were absolutely parallel to one edge of the diaphragm, which is rectangular in the ratio of 2:1 to give rise to deflection only in the shorter [011] direction. The applied pressure bends the diaphragm and a force acts on the bridge. The PECVD silicon nitride bridge was isotropically etched in a reactive ion etching (RIE) process with SF_6 (Fig. 2). In a second photolithographic process the diaphragm was defined from the rear side of the wafer, and was chemically etched in KOH. Nearby we designed an identical bridge on a full stable wafer to distinguish between the temperature dependence and the pressure dependence. A 30 nm thick chromium sputter layer was deposited on the bridge. The absorption coefficient was calculated to be 30% for 780 nm laser light. This thin sputter layer will not influence the elasticity of the bridge. The wafer was anodically bonded to a pyrex glass sample holder at a voltage of 1.4 kV with annealing at 350°C. Another sample was glued to a silicon sample holder.