length (the thickness of the $CoSi_2$ layer, 40 nm) and therefore strongly tapered space charge regions. Conditioned by high electric fields, electrons at the source side of the channel are injected into the space charge region and can pass it, before relaxation occurs. As a result, the effective current channel increases with increasing drain-source voltage.

S-parameter measurements were performed on PBTs with a grid periodicity of $0{\cdot}8\,\mu m$ ($b = d$) by an HF probe station and yielded a unity short-circuit current gain frequency $f_T =$ 6 GHz corrected for the pad impedances. This value is similar to the best results for overgrown Si-PBTs prepared in MBE by Ohshima *et al.* [3]. From our own computer simulations, solving the Poisson and the continuity equation, we would expect a transit frequency of 14 GHz for a transistor with $0{\cdot}4\,\mu m$ wide channels, a $CoSi_2$ stripe width of $0{\cdot}4\,\mu m$, and a source-crain distance h of $1\,\mu m$. Considering that the calculations yield data for the intrinsic transistor only, the discrepancy between measurement and calculation results from too high series resistances and the unoptimised high-frequency layout. Owing to high gate contact resistances and the relatively poor ratio between transconductance and drain conductance g_m/G_D of 5·6, the maximum oscillation frequency f_{max} reaches only 1·5 GHz for a transistor with $Z = 1$ mm total gate-finger length. To improve the high-frequency performance of the devices the main intrinsic parameter of PBTs, the channel length h, and the parasitic resistances have to be reduced.

Conclusions: We have fabricated buried monocrystalline $CoSi_2$ stripes embedded in Si by high-dose ion implantation with grating periodicities down to $0{\cdot}6\,\mu m$. These structures were used as gates in PBTs overgrown by silicon LPVPE. The highest obtained transconductance g_m is 70 mS/mm and transistors with a grid periodicity of $0{\cdot}8\,\mu m$ and gate width of 1 mm exhibit a unity current gain frequency f_T of 6 GHz.

Acknowledgment: We would like to thank J. Zillikens for technical support, H.-P. Bochem for SEM, M. Gebauer for ion implantations, and A. Fox for HF measurements.

30th November 1992

A. Schüppen, L. Vescan, M. Marso, A.V.D. Hart and H. Lüth (*Institut für Schicht- und Ionentechnik, Forschungszentrum Jülich, Leo-Brandt-Straße, W-5170 Jülich, Germany*)

H. Beneking (*Institut für Halbleitertechnik, Sommerfeldstraße, W-5100 Aachen, Germany*)

References

1 BOZLER, C. O., and ALLEY, G. D.: 'The permeable base transistor and its application to logic circuits', *Proc. IEEE.*, 1982, **70**, (1), pp. 46–52

2 RATHMAN, D. D., and NIBLACK, W. K.: 'Silicon permeable base transistors for low-phase-noise oscillator applications up to 20 GHz'. IEEE Microwave Theory and Techniques, MTT-S Dig., 1988, pp. 537–540

3 OSHIMA, T., NAKAMURA, N., NAKAGAWA, K., YAMAGUCHI, K., and MIYAO, M.: 'High-speed SiPBT with buried single crystal silicide electrode by MBE'. IEDM Tech. Dig., 1991, pp. 33–36

4 GRUHLE, A., BADOZ, P. A., CHEVALIER, F., HALIMAOUI, A., LALANNE, F., MOUIS, M., REGOLINI, J. L., VINCENT, G., and BENSAHEL, D.: 'Silicon etched-groove permeable base transistor fabrication with cutoff frequencies above 25 GHz', *Microelectron. Eng.*, 1991, **15**, pp. 27–30

5 MANTL, S.: 'Ion beam synthesis of epitaxial silicides: fabrication, characterization and applications', *Materials Science Reports*, 1992, **8**, (1, 2), pp. 1–95

6 ISHIBASHI, K., and FURUKAWA, S.: 'SPE-$CoSi_2$ submicrometer lines by lift-off using selective reaction and its application to a permeable base transistor', *IEEE Trans.*, 1986, **ED-33**, (3), pp. 322–327

7 SCHÜPPEN, A., MANTL, S., VESCAN, L., WOIWOD, S., JEBASINSKI, R., and LÜTH, H.: 'Permeable base transistors with ion-implanted $CoSi_2$-gate', *Materials Science and Engineering*, 1992, **B12**, pp. 157–160

8 SCHÜPPEN, A., VESCAN, L., JEBASINSKI, R., HART, A. V. D., and LÜTH, H.: 'Effect of doping profiles on $Si/CoSi_2$ permeable base transistors', *Microelectron. Eng.*, 1992, **18**, (3), pp. 259–266

STRUCTURE FOR TIME-VARYING PARAUNITARY FILTER BANKS WITH PERFECT RECONSTRUCTION

R. L. de Queiroz and K. R. Rao

Indexing terms: Signal processing, Filters

A perfect reconstruction structure for a time-varying FIR paraunitary filter bank is developed, based on a known factorisation procedure. It allows the implementation of any uniform paraunitary filter bank, as well as distortion-free switchings from one filter bank to another.

Introduction: Multirate filter banks are well known powerful tools in modern digital signal processing [1–4]. They are generally thought of as stationary forms, and several perfect reconstruction (PR) conditions have been presented under different viewpoints [2–4]. Recently, Nayebi *et al.* [5] presented a preliminary study on the structure of time-varying filter banks.

Consider a uniform FIR paraunitary filter bank (PUFB) with M filters, each one of length L, with $L = NM$, where N is an even integer. The M analysis filters are time-reversed versions of the synthesis filters [3]. If the analysis and synthesis filters are represented by $f_m(n)$ and $g_m(n)$, respectively, for $m = 0, 1, \ldots, M-1$ and $n = 0, 1, \ldots, L-1$, we can define a transform matrix $\boldsymbol{P}$ [3], of size $M \times L$ with elements p_{mn} as $p_{mn} = g_m(n) = f_m(L-1-n)$. $\boldsymbol{P}$ can be also decomposed into $NM \times M$ matrices as $\boldsymbol{P} = [\boldsymbol{P}_0 \boldsymbol{P}_1 \ldots \boldsymbol{P}_{N-1}]$. The PR conditions can be described as [3]

$$\sum_{m=0}^{N-1-l} \boldsymbol{P}_m \boldsymbol{P}_{m+l}^T = \delta(l)\boldsymbol{I}_M \tag{1}$$

for $l = 0, 1, \ldots, N-1$, where $\delta(l) = 1$ for $l = 0$, and $\delta(l) = 0$, otherwise. Using a factorisation of $\boldsymbol{P}$ we will develop a PR structure for time-varying PUFB.

Factorisation: Let $\boldsymbol{X}$ and $\boldsymbol{Y}$ be time and frequency vectors of infinite length, respectively. The transform $\tilde{\boldsymbol{P}}$ that maps $\boldsymbol{X}$ into $\boldsymbol{Y}$ is a block circulant matrix.

$$\tilde{\boldsymbol{P}} = \begin{pmatrix} \ddots & & & \ddots & & & \\ & \boldsymbol{P}_0 & \boldsymbol{P}_1 & \ldots & \boldsymbol{P}_{N-1} & \boldsymbol{0} & \boldsymbol{0} \\ & \boldsymbol{0} & \boldsymbol{P}_0 & \boldsymbol{P}_1 & \ldots & \boldsymbol{P}_{N-1} & \boldsymbol{0} \\ & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{P}_0 & \boldsymbol{P}_1 & \ldots & \boldsymbol{P}_{N-1} \\ & & & & \ddots & & \ddots \end{pmatrix} \tag{2}$$

If $\boldsymbol{P}$ is a PR PUFB, then

$$\boldsymbol{Y} = \tilde{\boldsymbol{P}}\boldsymbol{X} \quad \text{and} \quad \boldsymbol{X} = \tilde{\boldsymbol{P}}^T \boldsymbol{Y} \tag{3}$$

$\tilde{\boldsymbol{P}}$ can be viewed as the result from the overlapping of the transform matrices, for each block.

The transform matrix $\boldsymbol{P}$ can be viewed as a transform that maps the elements of $\mathscr{R}^L$ (L-tuples over the real field) into a particular M-dimensional subspace Λ, having its orthogonal basis as the rows of $\boldsymbol{P}$. We can find a particular factorisation for $\boldsymbol{P}$ by:

(i) finding a remaining set of $L - M$ orthogonal basis of $\mathscr{R}^L$

(ii) factorising the corresponding $L \times L$ orthogonal transform into plane rotations

(iii) retaining only the parts important to $\boldsymbol{P}$.

Any orthogonal transform inside $\mathscr{R}^L$ can be implemented using $\binom{L}{2} = L(L-1)/2$ planar rotations (one for each possible pair of orthogonal basis). Alternatively, the factorisation can be efficiently achieved through the analysis of the polyphase lossless matrix [6] representing the PR PUFB. Actually, with N orthogonal factors separated by delay matrices, any PUFB can be implemented. This is a known result, which, translated to the notation of transform matrices, is

$$\tilde{P} = \tilde{A}_{1,D}\tilde{A}_{1,P}\tilde{A}_{2,D}\tilde{A}_{2,P}\ldots\tilde{A}_{N,D} \quad (4)$$

where $\tilde{A}_{n,P}$ are permutation matrices to account for the delays (noting that we are using a noncausal representation). The matrices $\tilde{A}_{n,D}$ are block-diagonal (each block is $M \times M$) as

$$\tilde{A}_{n,D} = \mathrm{diag}\{\ldots R_n, R_n, R_n \ldots\} \quad (5)$$

with R_n having the same structure devised for each factor of the lossless transfer matrix [6]. Actually, R_n is an orthogonal matrix which can be implemented with $M - 1$ plane rotations. As an exception, R_1 is a general orthogonal matrix requiring $M(M-1)/2$ plane rotations. Each rotation has an associated angle which is a free parameter in the design of a PUFB. This general decomposition into sparse matrices is not unique, but is minimal in terms of total number of rotations [6].

Orthogonality under time variations: Suppose the angles in each R_n in eqn. 5 are changed along the time index. More precisely, suppose it is written as

$$\tilde{A}_{n,D} = \mathrm{diag}\{\ldots R_n(k-1), R_n(k), R_n(k+1)\ldots\} \quad (6)$$

Because only the angles are changed, each matrix is still orthogonal and PR is assured using the same flow graph for analysis or synthesis. The analysis–synthesis process is now described by a matrix $\tilde{P}$, where

$$\tilde{P} = \begin{pmatrix} \ddots & & \ddots & & & \\ P_0(k-1) & \ldots & P_{N-1}(k-1) & 0 & 0 & \\ 0 & P_0(k) & \ldots & P_{N-1}(k) & 0 & \\ 0 & 0 & P_0(k+1) & \ldots & P_{N-1}(k+1) & \\ & & & \ddots & & \ddots \end{pmatrix} \quad (7)$$

with

$$P(k) = [P_0(k) \quad P_1(k) \quad \ldots \quad P_{N-1}(k)] \quad (8)$$

This means that $P(k)$ contains the instantaneous filter bank impulse responses. In time-varying systems, we have to choose an index k and find the PR equations for it, noting that eqn. 1 is no longer valid. It is possible to show that the PR conditions for the time-varying case can be written as

$$\sum_{m=0}^{N-1-l} P_m(k)P_{m+l}^T(k-l) = \sum_{m=0}^{N-1-l} P_{m+l}(k)P_m^T(k+l) = \delta(l)I_M \quad (9)$$

for $l = 0, 1, \ldots, N-1$, yielding $2N-1$ independent matrix equations.

Conclusive analysis: With the proper choice of angles in the factorised form of $P(k)$, we are able to implement any steady PUFB, with M bands and filters with length up to L. Therefore, we can change the angles and switch between any two PUFBs. $P(k)$ has compact support (contains FIR filters) and will 'forget' past conditions, acting as the new filter bank, after some time. Clearly, there would be a transition region where none of the filter bank responses is achieved. At each instant we can calculate $P(k)$ which will provide the intermediary frequency response. However, the system is naturally PR, even in transitions, guaranteeing distortionless processing.

The main idea is to switch between two known PUFBs at a time. For this, each of them has to be expressed in its factorised form. To change the filter bank at instant k, we can set all angles in all $R_n(i)$ $(i \geq k)$ to their new values. Finally, note that any orthogonal block transform $(L = M)$ can be implemented, because a PUFB having filters whose length lies between M and L belongs to the set of all PUFBs whose filters have length L. This can be seen by constraining marginal elements of the filters to be zero. Therefore, it is possible to switch between lapped and block transforms among other possibilities. Even the identity matrix can be used, causing the transform to be bypassed (copying input to output), while maintaining PR in transitions.

Acknowledgments: This work was supported in part by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Brazil, under Grant 200.804-90-1.

20th November 1992

R. L. de Queiroz and K. R. Rao (*Electrical Engineering Department, University of Texas at Arlington, Box 19016, Arlington, TX, 76019, USA*)

References

1 CROCHIERE, R. E., and RABINER, L. R.: 'Multirate digital signal processing' (Prentice-Hall, USA, 1983)

2 VAIDYANATHAN, P. P.: 'Multirate digital filters, filter banks, polyphase networks and applications: a tutorial', *Proc. IEEE.*, 1990, **78**, pp. 56–93

3 MALVAR, H. S.: 'Signal processing with lapped transforms' (Artech House, USA, 1992)

4 VETTERLI, M., and LE GALL, D.: 'Perfect reconstruction filter banks: some properties and factorizations', *IEEE Trans.*, 1989, **ASSP-37**, (7), pp. 1057–1071

5 NAYEBI, K., BARNWELL, T. P., and SMITH, M. J.: 'Analysis–synthesis systems with time-varying filter bank structures'. Proc. Int. Conf. on Acoust., Speech, Signal Processing, 1992, vol. IV, pp. 617–620

6 DOĞANATA, Z., VAIDYANATHAN, P. P., and NGUYEN, T. Q.: 'General synthesis procedures for FIR lossless transfer matrices, for perfect reconstruction multirate filter banks applications', *IEEE Trans.*, 1988, **ASSP-36**, (10), pp. 1561–1574

COMMENT

PERFORMANCE OF CROSSBAR INTERCONNECTION NETWORKS IN THE PRESENCE OF 'HOT SPOTS'

R. Y. Awdeh and H. T. Mouftah

Pombortsis and Halatsis have considered the performance of crossbar interconnection networks in the presence of hot spot traffic conditions [A]. They have assumed an $N \times N$ crossbar operating in a synchronous mode, where each processor issues r requests to the shared memory per network cycle $(0 \leq r \leq 1)$. A fraction h $(0 \leq h \leq 1)$ of all references are aimed at a specific memory module MM_h (the hot spot memory module), i.e. each processor emits $r(1-h)$ requests uniformly over all N MMs, and rh requests to MM_h.

It was stated that the rate of requests at MM_h due to hot spot traffic is

$$P_h = 1 - (1 - rh)^N \quad (1)$$

and due to uniform background traffic is

$$P_u = 1 - \left[1 - \frac{r(1-h)}{N}\right]^N \quad (2)$$

Based on the assumption that requests are random and the requests generated by a processor are independent of the requests generated by another processor, it was concluded that P_h and P_u are statistically independent, and thus the total rate of requests at MM_h is

$$P_t = P_h + P_u - P_hP_u = 1 - (1 - rh)^N\left[1 - \frac{r(1-h)}{N}\right]^N \quad (3)$$

However, we think that the above procedure of obtaining P_t is incorrect, and that the statistical independence assumption between the rate of requests at MM_h due to hot spot traffic and those due to uniform background traffic is not valid.