様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

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研究課題名（和文）不揮発メモリの書込みビット数を厳密に最小化する符号化とノーマリオフ計算への応用

研究課題名（英文）Bit-write minimizing codes for non-volatile memories and their application to normally-off computing

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研究成果の概要（和文）：ノーマリオフ計算の中心的役割を果たすものに不揮発メモリがある．不揮発メモリは，通常の揮発メモリと同様な動作速度を持った上で，電源オフ状態でメモリ内容を消失しないことを特長とする．ところが不揮発メモリは，ビット読出しに比べ，ビット書込みエネルギーが1 桁以上も大きく，その成否は「不揮発メモリの書込みビットをいかに削減するか」にある．本研究では，誤り訂正符号の見方を逆転させ，真値と各誤り値の「差分」こそが情報を持つという挑戦的なアイデアのもと，実際に書込みビット数と誤り訂正を両立する符号を構築した．さまざまなアプリケーションプログラムに提案した符号を適用し，提案した符号の有効性を確認した．

研究成果の学術的意義や社会的意義
不揮発メモリの活用には，いかに書込みビット数を削減するかが大きな焦点となっていた．加えて，メモリセルは誤りを起こすことがあり，書込み削減と誤り訂正とを両立することが実用上，大きな意味を持つ．本研究で提案した書込みビット数と誤り訂正を両立する符号は，理論的に誤り訂正能力を保持したままビット書込み数を抑えることを証明したと同時に，さまざまなアプリケーションプログラムに適用した結果，実際にビット書込み数の削減を確認している．しかも誤り訂正能力は，もとの符号のものと同一であることも理論的に示されている．これらは，不揮発メモリを用いたノーマリオフ計算の発展に大きな意味を持つものと考えられる．

研究成果の概要（英文）：Non-volatile memories play an important role in normally-off computing. Non-volatile memories have almost the same operation speed as the normal memories and its cell contents remain even if they are switched-off. However, non-volatile memories sometimes consume 10 times or more energy in writing compared to normal memories and how to reduce the number of writing bits is one of the largest problems. In this research, we developed bit-write reducing and error-correcting codes for non-volatile memories based on effectively clustering error-correcting codes. Experimental evaluation results demonstrate that the proposed bit-write reducing and error-correcting codes can be effectively applied to various classes of application programs.

研究分野：集積システム設計

キーワード：不揮発メモリ　書込み削減符号　符号化　ノーマリオフ計算

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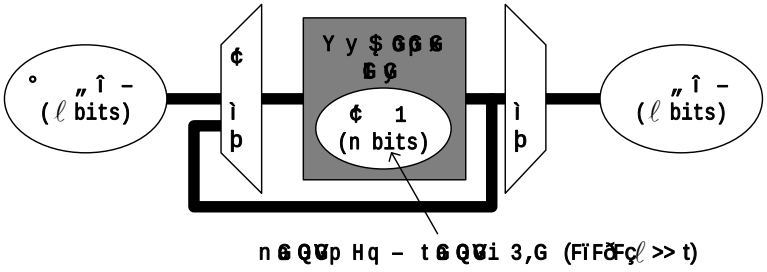
[illegible] MRAM & Magnetoresistive Random Access Memory [illegible] STT-RAM & Spin Transfer Torque Random Access Memory [illegible] SRAM [illegible]



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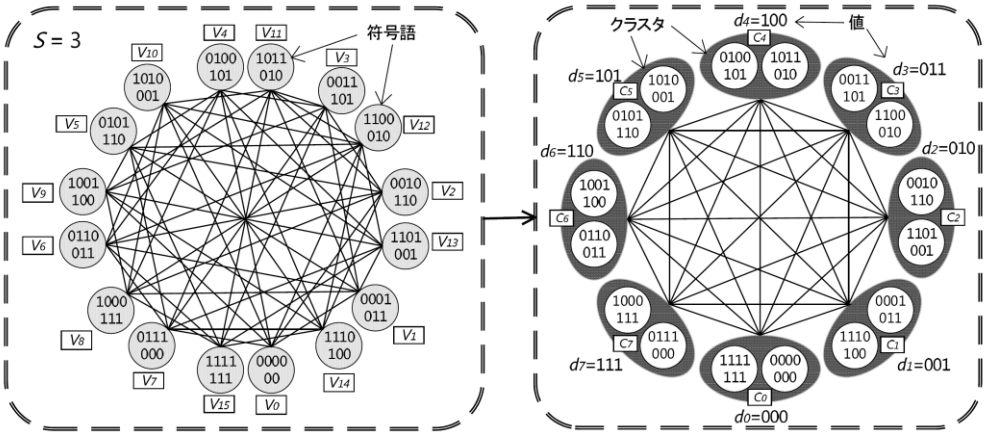
t $\boldsymbol{S}$ k_p $\boldsymbol{S}$ $v_0, \cdots, v_{2^{k_p}-1}$ $\boldsymbol{S}$ v_i n $\boldsymbol{S}$ k_p $\boldsymbol{t}$ $\boldsymbol{S}$ n $\boldsymbol{S}$ $2t+1$ t $\boldsymbol{S}$ $(n, k_p, 2t+1)$ $S \geq 2t+1$ $(n, k_p, 2t+1)$ $\boldsymbol{S}$

1. [illegible] $v_0, \cdots, v_{2^{k_p}-1}$ $\boldsymbol{S}$
2. [illegible] v_i, v_j S $\boldsymbol{t}$ $e_{ij} = (v_i, v_j)$

[illegible] $V = \{v_0, \cdots, v_{2^{k_p}-1}\}$ $\boldsymbol{t}$ E $\boldsymbol{S}$ S-[illegible] $G = (V, E)$ [illegible] S-[illegible] r $k_r = k_p - r$ $\boldsymbol{S}$ [illegible] V c_i $i = 0, \cdots, 2^{k_r-1}$ $\boldsymbol{S}$



W 2 S-

(C1) $c_0 \cup \cdots \cup c_{2^{k_r-1}} = V$
(C2) $c_i \cap c_j = \emptyset \ \ (i \neq j)$
(C3) $|c_i| = 2^r$

[illegible] (C1)=(C3)[illegible] $C = \{c_0, \ldots, c_{2^{k_r-1}-1}\}$
S c_i, c_j C S S c_i, c_j (F1), (F2)
6SMA* c_i, c_j t $e'_{ij} = (c_i, c_j)$

(F1) [illegible] c_i S v_k c_j S S v_l t
e_{kl} S
(F2) [illegible] c_j S v_l c_i S S v_k t
e_{lk} S

[illegible] (F1)í (F2) S S -[illegible] [illegible]
[illegible]7 C S t E'
S C t E' $G' = (C, E')$
S 2 [illegible]M7
$D = \{d_0, \cdots, d_{2^{k_r-1}}\}$ k_r S $d_0 = 00 \cdots 00, d_1 = 00 \cdots 01, \ldots, d_{2^{k_r-1}} =$
$11 \cdots 11$ S $d_i \in D$ $c_i \in C$ S $c_i \in C$ S
$d_i \in D$ S

1 ˝ d_i, d_j c_i, c_j S c_i S v_k
S $G' = (C, E')$ S c_j S S v_l
v_k v_l S S

0É [illegible] c_i, c_j S St S
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(Ô 1 ˝ d_j t v_k d_j t v_l S S
$G' = (C, E')$ S d_j v_k d_j v_l
S S

2 [illegible] c_j S v_k t

0É [illegible] v_k $(n, k_p, 2t+1)$ S S

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[illegible] c_i S d_j t
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$(n, k_p, 2t+1)$ LSECC vS(M r $k_r = k_p - r$ $(n, k_r, 2t+1, r)$-REC LSECC @ $11\cdots11$ $(n, k_r, 2t+1, r)$-Relaxed-REC Relaxed-REC

1. n k_r S LSECC b5M Relaxed-REC q– i3ş $(n - \lceil k_p/2 \rceil)$ S
2. Relaxed-REC 10Gc t S
3. Relaxed-REC i3ş REC IC^

/†1 _ REC Relaxed-REC ArU MmZ5 $k_r = 8$ $t = 2$ S

S 1 (37, 8, 5, 8)-REC i3ş 7.18 KZ (26, 8, 5, 8)-relaxed-REC 5.83

/†1 REC Relaxed-REC A

	n	t	qi3ş	qI3ş	i3ş
(15,7,5)-BCH (5,1,5)-o	20	2	20	5	10.0
(23,8,5,1)-REC	23	2	11	5	8.92
(25,8,5,2)-REC	25	2	12	5	8.67
(29,8,5,3)-REC	29	2	12	5	7.80
(37,8,5,4)-REC	37	2	10	5	7.18
(17,8,5,1)-Relaxed-REC	17	2	8	5	6.77
(19,8,5,2)-Relaxed-REC	19	2	9	5	6.89
(21,8,5,3)-Relaxed-REC	21	2	9	5	6.41
(26,8,5,4)-Relaxed-REC	26	2	8	5	5.83

)F8 MediaBench SimpleScalar KS P1 ZBKS 3ş KS /†2 _ i3ş)Ý (17, 8, 5, 1)-relaxed-REC ZBKS (23, 8, 5, 1)-REC ZBKS 20.6% b i 3ş KS (26, 8, 5, 8)-relaxed-REC ZBKS (15, 7, 5)-BCH +(5, 1, 5)-o ZBKS 38.9%vbi 3ş KS

/†2 KS7b i3ş PÝ

	adpcmE	adpcmD	epicE	epicD	g721E	g721D
(15, 7, 5)-BCH 符号 + (5, 1, 5) 反復符号	2,902,865 (1.00)	1,022,642 (1.00)	1,213,777 (1.00)	670,655 (1.00)	3,030,135 (1.00)	1,140,475 (1.00)
(23, 8, 5, 1)-REC	2,492,757 (0.86)	974,215 (0.95)	1,240,812 (1.02)	695,669 (1.04)	2,625,590 (0.87)	1,073,272 (0.94)
(25, 8, 5, 2)-REC	2,303,056 (0.79)	929,465 (0.91)	1,168,265 (0.96)	649,003 (0.97)	2,426,246 (0.80)	1,012,208 (0.89)
(29, 8, 5, 4)-REC	2,146,736 (0.74)	873,537 (0.85)	1,111,116 (0.92)	629,212 (0.94)	2,264,785 (0.75)	929,645 (0.82)
(37, 8, 5, 8)-REC	2,085,224 (0.72)	811,245 (0.79)	1,038,296 (0.86)	592,397 (0.88)	2,199,998 (0.73)	888,672 (0.78)
(17, 8, 5, 1)-relaxed-REC	2,046,513 (0.70)	767,730 (0.75)	985,159 (0.81)	563,423 (0.84)	2,159,348 (0.71)	847,269 (0.74)
(19, 8, 5, 2)-relaxed-REC	1,993,295 (0.69)	774,639 (0.76)	996,721 (0.82)	570,375 (0.85)	2,105,284 (0.69)	854,668 (0.75)
(21, 8, 5, 4)-relaxed-REC	1,862,289 (0.64)	736,402 (0.72)	937,886 (0.77)	537,731 (0.80)	1,965,608 (0.65)	792,833 (0.70)
(26, 8, 5, 8)-relaxed-REC	1,774,395 (0.61)	677,714 (0.66)	878,235 (0.72)	510,916 (0.76)	1,873,010 (0.62)	745,191 (0.65)

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