Reversible MOS chips

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Workshop topics addressed:

6. Design principles in MOS circuits

8. Classical mode (i.e. not quantum mode)
   of MOS reversible computing
Feynman gate

Toffoli gate

Fredkin gate
FEYNMAN gate

TOFFOLI gate

FREDKIN gate
Implementation of
(a) FEYNMAN gate
(b) TOFFOLI gate
(c) FREDKIN gate.
A witch in MOS consists of

(a) an n-type MOS transistor and
(b) a p-type MOS transistor,
(c) together a ‘transmission gate’. 
Microscope photograph (24 μm × 36 μm) of FEYNMAN gate and TOFFOLI gate (8 and 16 transistors, respectively).
Microscope photograph (140 µm × 120 µm) of 2.4-µm 4-bit reversible ripple adder (192 transistors).
Microscope photograph (140 $\mu$m $\times$ 230 $\mu$m) of 0.35-$\mu$m 8-bit Cuccaro adder (392 transistors).
Microscope photograph (680 $\mu$m $\times$ 380 $\mu$m) of 0.35-$\mu$m 4-data H.264 transform (1,648 transistors).
Microscope photograph (680 \( \mu \text{m} \times 380 \mu \text{m} \)) of 0.35-\( \mu \text{m} \) 4-data H.264 transform (1,648 transistors).

\[
\begin{pmatrix}
P \\ Q \\ R \\ S
\end{pmatrix}
= 
\begin{pmatrix}
1 & 1 & 1 & 1 \\
2 & 1 & -1 & -2 \\
1 & -1 & -1 & 1 \\
1 & -2 & 2 & -1
\end{pmatrix}
\begin{pmatrix}
A \\ B \\ C \\ D
\end{pmatrix}
\]
Oscilloscope view of 0.35 $\mu$m full adder.
\[ Q \approx CV^2 \]
\[ Q \approx \frac{RC}{\tau} CV^2 \]
Moore’s law for dimensions $L$, $W$, and $t$ threshold voltage $V_t$ heat dissipation $Q$

<table>
<thead>
<tr>
<th>technology $(\mu m)$</th>
<th>$L$ $(\mu m)$</th>
<th>$W$ $(\mu m)$</th>
<th>$t$ (nm)</th>
<th>$V_t$ (V)</th>
<th>$Q$ (fJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
<td>42.5</td>
<td>0.9</td>
<td>38</td>
</tr>
<tr>
<td>0.8</td>
<td>0.8</td>
<td>2.0</td>
<td>15.5</td>
<td>0.75</td>
<td>2.0</td>
</tr>
<tr>
<td>0.35</td>
<td>0.35</td>
<td>0.5</td>
<td>7.4</td>
<td>0.6</td>
<td>0.30</td>
</tr>
<tr>
<td>0.13</td>
<td>0.12</td>
<td>0.16</td>
<td>3</td>
<td>0.35</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Energy dissipation per computational step:

$$Q \approx \frac{1}{2} CV_t^2 ,$$

where

$$C \approx \varepsilon_0 \varepsilon \frac{WL}{t}$$

We compare with the Landauer quantum

$$kT \log(2) \approx 3 \, z \, J = 0.000 \, 003 \, fJ .$$
A perspective from the 2003 ITRS
= International Technology Roadmap of Semiconductors.
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   of MOS reversible computing
From classical reversible to quantum?
From classical reversible to quantum?

\[
\begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 \\
0 & 0 & 1 & 0
\end{pmatrix}
\text{ versus }
\begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1/2 + i/2 & 1/2 - i/2 \\
0 & 0 & 1/2 - i/2 & 1/2 + i/2
\end{pmatrix}
\]

with respective symbols

\[\begin{array}{c}
\bullet \\
\circ \\
\end{array}
\text{ versus }
\begin{array}{c}
\bullet \\
\checkmark \\
\end{array}\]
Probability distribution for logic 1
Probability distribution for logic 0

-2 volt  0  2 volt

voltage
Probability distribution
during classical transition
from logic 0 to logic 1
Probability distribution
during classical transition
from logic 0 to logic 1
Probability distribution during classical transition from logic 0 to logic 1
Probability distribution during classical transition from logic 0 to logic 1
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Probability distribution during classical transition from logic 0 to logic 1

![Graph showing probability distribution with voltage axis ranging from -2 volts to 2 volts.](image-url)
Probability distribution
during quantum transition
from logic 0 to logic 1
Probability distribution during quantum transition from logic 0 to logic 1
Probability distribution during quantum transition from logic 0 to logic 1.
Probability distribution during quantum transition from logic 0 to logic 1
Probability distribution during quantum transition from logic 0 to logic 1
Probability distribution
during quantum transition
from logic 0 to logic 1
Probability distribution during quantum transition from logic 0 to logic 1