Ternary Content Addressable Memory

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Outline

- Introduction
- Core cell
- Hybrid - type matchline structure
- Matchline sensing scheme
- Searchline sensing scheme
- Conclusion
- Reference
Introduction

- Conceptual view of a CAM.
  - Single cycle throughput → high speed.
  - Popular in network routers.
  - IP4 vs. IP6 → larger capacity CAMs.
  - Power consumption issue.
  - Leakage current in advanced technologies.
  - Conventional CAM search operation.
    - Priority encoder is used.
Introduction – cont.

- Two types of CAM cells: Binary vs. Ternary
  - Both can store 0 and 1 state.
  - Ternary CAMs have additional “X” state.

- CAM cell = Storage + Comparison Circuit.
  - Storage circuit is implemented by SRAM.
  - Comparison circuit is implemented in different manners corresponding to each cell types.
    - NOR type, NAND type, Hybrid type etc.

If don’t-care data equals to 1, the match-line (ML) will bypass and be discharged to ground.
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Core cell

- NOR cell: Multiple cells are connected in parallel forming a word by shorting the ML together with adjacent cells.
  - ML remains high in match state and discharge when miss.
  - The comparison circuit is a XNOR logic gate.
  - High search speed, high power consumption.

<table>
<thead>
<tr>
<th></th>
<th>ML</th>
<th>SL=0</th>
<th>SL=1</th>
</tr>
</thead>
<tbody>
<tr>
<td>D=0</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>D=1</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
NAND cell: Multiple cells are connected in series forming a word by joining the \( ML_n \) and \( ML_{n+1} \).
- ML discharges to ground in match state and remains high in miss.
- The comparison circuit is a XNOR logic gate.
- Power efficient with the penalty of low speed.
Core cell – cont.

- Ternary cell: stores an additional don’t care value.

<table>
<thead>
<tr>
<th>Stored Value</th>
<th>Stored</th>
<th>Search Bit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1 0 1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0 1 0</td>
</tr>
<tr>
<td>X</td>
<td>1</td>
<td>1 0 0</td>
</tr>
</tbody>
</table>

- Ternary core cell for NOR-type cell

- Ternary core cell for NAND-type cell
Core cell – cont.

- Modified Ternary cell:
  - Reducing leakage power in advanced technology.
  - Destroy the prefix data to reduce the LP when state is “X”.
  - Without performance penalty.
  - Two main part of leakage current:
    - Subthreshold leakage
    - Gate leakage

<table>
<thead>
<tr>
<th>M</th>
<th>D</th>
<th>S</th>
<th>State</th>
<th>ML</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>H</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>H</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>L</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>L</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>X</td>
<td>H</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>X</td>
<td>H</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>X</td>
<td>H</td>
</tr>
</tbody>
</table>

Conventional TCAM cell components and the corresponding state table
Core cell – cont.

- Modified Ternary cell (cont.) :
  - Proposed scheme: Dynamic Power Source (DPS)
  - Extension of power gated scheme.
    - No need of extra gated MOS → saving area.
    - Can reduce subthreshold leakage current largely.
  - Modified XOR logic to prevent short-circuit path in comparison circuit.

Conventional TCAM cell components

DPS\textsubscript{VDD} Implementation

DPS\textsubscript{GND} Implementation

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Hybrid - type matchline structure

- Combine the performance advantages of the NOR-type CAM and the power efficiency of the NAND-type CAM.
- With a marginal area overhead and largely reduces dynamic power and improves search performance.
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Matchline sensing scheme

**Conventional matchline sensing scheme:**
- Power issue severe.

![Conventional matchline sensing scheme diagram](image)

**Low swing scheme:**
- Reduce ML voltage swing \(\rightarrow\) reduce dynamic power.
- Potentially increasing speed.
- Challenge: no externally generated referenced voltage.

![Low swing scheme diagram](image)
Matchline sensing scheme – cont.

- **Selective precharge scheme:**
  - A 144-bit word divided into 3-bit part and remaining 141-bit part.
  - Saves about 88% of the matchline power.
  - Worst case: all initial bits matched, thus eliminating any power saving.

- **Pipeline scheme:**
  - Extension of selective precharge scheme.
  - Drawbacks:
    - Increased latency and area overhead.
  - Enable the use of hierarchical searchlines.
Matchline sensing scheme – cont.

- **Butterfly matchline scheme:**
  - Increasing parallelism of search operation → obtains high speed.
  - XOR-based conditional keeper → provides noise tolerant.
  - Interlaced pipeline connection → reduces power consumption.

<table>
<thead>
<tr>
<th>ML precharge</th>
<th>Floating node</th>
<th>Control Signal of keeper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Low</td>
<td>Low, to speed up the process of pre-charge</td>
</tr>
<tr>
<td>Low</td>
<td>High</td>
<td>High, to avoid the impact on performance at the very beginning of evaluation</td>
</tr>
<tr>
<td>High</td>
<td>Low</td>
<td>High, keeper should be off</td>
</tr>
<tr>
<td>High</td>
<td>High</td>
<td>Low, keeper should be activated to enhance the capability of noise immunity</td>
</tr>
</tbody>
</table>

Critical path

![Diagram of XOR-based Conditional Keeper](image)
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Searchline sensing scheme

- **Conventional sensing scheme:**
  - Apply with precharge matchline high scheme.
  - Power consumption is big and searchline cap is large → bad.

- **Eliminating searchline precharge scheme:**
  - For matchline precharged low scheme.
  - In typical case, 50% reduction in searchline power.
Searchline sensing scheme

Don’t care based Hierarchical searchline:

- Decrease the switching capacitances and switching activities.
- No search time overhead.
- Global-Searchline (GBL) vs. Local-Searchline (LSL).
  - GBLs activate every cycle.
  - LSLs activate depending on don’t care cells.
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Conclusion

- Two basic CAM cells, NOR/NAND type.
- Differences between CAM and TCAM.
- Power saving techniques based on cell structure, matchline scheme, searchline scheme.
- Dynamic power reduction is not enough in advanced technology, leakage power reduction has become more and more important.
- 3D stacked TCAM is another research in the future.
  - A Low-Power Monolithically Stacked 3D-TCAM, ISCAS, 2008
Reference