A Deeper Dive: Where (And How and Why) to Implement Solid-State Storage

Dennis Martin
President, Demartek
Solid-State Storage

Agenda

- About Demartek
- Solid-state storage overview
- Types of NAND flash
- NAND flash endurance and performance
- SSD form factors – devices and storage systems
- Data placement strategies (caching and tiering)
- Performance results comparison – SSD vs. HDD
About Demartek

- Industry analysis with on-site test lab
- Lab includes servers, networking and storage infrastructure
  - Fibre Channel – 4, 8 & 16 Gbps
  - Ethernet – 1 & 10 Gbps: NFS, SMB (CIFS), iSCSI & FCoE
  - Servers – 8+ cores, large RAM
  - Virtualization – ESX, Hyper-V, Xen
- We prefer to run real-world applications to test servers and storage solutions
  - Currently testing various SSD, 16GFC and other technologies
- Website: www.demartek.com
Solid-State Storage Overview

● Uses memory as the storage media and appears as a disk drive to the operating system in most cases
  - Some motherboards allow dedicated SSD to act as a cache or other functions
● Very fast, no moving parts
● Variety of form factors
● Prices dropping
● Some SSDs use DRAM and NAND flash together
● Capacities doubling almost yearly
New Acronyms and Buzzwords

- **SSD** – Solid state drive (or disk)
- **SSS** – Solid-state storage
- **SLC** – Single-level cell
- **MLC** – Multi-level cell
- **P-E Cycle** – Program-erase cycle
- **EFD** – Enterprise flash drive
- **SCM** – Storage class memory
Dynamic Random Access Memory (DRAM) SSD

- Same type of memory that is in servers
- Volatile – Needs battery or disk backup
- Highest IOPS – 100K – 5M+
- Latencies in microseconds
- Can be used as a cache in front of other storage
NAND Flash – What is It?

- A specific type of EEPROM
  - EEPROM – Electrically erasable programmable read-only memory
  - The underlying technology is a floating-gate transistor that holds a charge
- Bits are erased and programmed in blocks
  - Process is known as the program-erase (P-E) cycle
  - Flash blocks are typically 4KB, some larger
- Non-volatile
- Quiet, low-power, low-weight, low-heat
- Types – SLC & MLC
NAND Flash SSD Performance and Capacities

- **IOPS**
  - 10K – 250K reads per device
    - Enterprise HDDs – 100-200 IOPS
    - Desktop HDDs – < 100 IOPS
  - Writes are generally slower than reads

- **Current maximum capacities available**
  - Individual devices
    - Drive form factor – 1.6 TB
    - PCIe card – 5.1 TB
    - DIMMs – 480 GB
  - Arrays – Up to 1 PB (“all-SSD” arrays)
# NAND Flash – SLC vs. MLC

- **Single-level cell (SLC)** – One bit per cell
- **Multi-level cell (MLC)** – Two or more bits per cell (MLC-x)
  - **Triple-level cell (TLC)** – Three bits per cell

<table>
<thead>
<tr>
<th></th>
<th>SLC</th>
<th>MLC-2</th>
<th>MLC-3</th>
<th>MLC-4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bits per cell</strong></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td><strong>Performance</strong></td>
<td>Fastest</td>
<td></td>
<td></td>
<td>Slowest</td>
</tr>
<tr>
<td><strong>Endurance</strong></td>
<td>Longest</td>
<td></td>
<td></td>
<td>Shortest</td>
</tr>
<tr>
<td><strong>Capacity</strong></td>
<td>Smallest</td>
<td></td>
<td></td>
<td>Largest</td>
</tr>
<tr>
<td><strong>Error Prob.</strong></td>
<td>Lowest</td>
<td></td>
<td></td>
<td>Highest</td>
</tr>
<tr>
<td><strong>Price per GB</strong></td>
<td>Highest</td>
<td></td>
<td></td>
<td>Lowest</td>
</tr>
<tr>
<td><strong>Applications</strong></td>
<td>Enterprise</td>
<td>Enterprise / Consumer</td>
<td>Consumer</td>
<td>Consumer</td>
</tr>
</tbody>
</table>
NAND Flash – Endurance

● Single-level cell (SLC)
  - SLC typical life of 100,000 write cycles

● Multi-level cell (MLC)
  - MLC typical life 10,000 or fewer write cycles
    ▪ MLC-2 – 3,000 – 10,000 write cycles
    ▪ MLC-3 – 300 – 3,000 write cycles
  - “Enterprise MLC” (eMLC) – 20,000 – 30,000 write cycles
    ▪ Based on MLC-2
    ▪ Better name is probably “Endurance MLC”
NAND Flash – Endurance Specifications

- JEDEC Standards (www.jedec.org)
  - Joint Electron Devices Engineering Council
  - JESD218A – SSD Requirements and Endurance Test Method
  - JESD219 – SSD Endurance Workloads

- SSD endurance classes and requirements

<table>
<thead>
<tr>
<th>Application Class and Workload</th>
<th>Active Use (power on)</th>
<th>Retention Use (power off)</th>
<th>Functional Failure Rqmt. (FFR)</th>
<th>UBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Client</td>
<td>40°C 8 hrs/day</td>
<td>30°C 1 year</td>
<td>≤3%</td>
<td>≤10^{-15}</td>
</tr>
<tr>
<td>Enterprise</td>
<td>55°C 24 hrs/day</td>
<td>40°C 3 months</td>
<td>≤3%</td>
<td>≤10^{-16}</td>
</tr>
</tbody>
</table>
## NAND Flash – Performance vs. Cost

<table>
<thead>
<tr>
<th>Storage Type</th>
<th>$/GB</th>
<th>$/IOPS</th>
<th>IOPS/watt</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSD (SLC)</td>
<td>$5 – $40</td>
<td>$0.005 – $0.15</td>
<td>1000 – 15000</td>
</tr>
<tr>
<td>SSD (MLC)</td>
<td>$0.63 – $4</td>
<td>$0.004 – $0.05</td>
<td>1000 – 15000</td>
</tr>
<tr>
<td>HDD (enterprise)</td>
<td>$0.50 – $1</td>
<td>$1 – $3</td>
<td>10 – 30</td>
</tr>
<tr>
<td>HDD (desktop)</td>
<td>$0.05 – $0.37</td>
<td>$1 – $4</td>
<td>10 – 40</td>
</tr>
</tbody>
</table>

- SSDs are dollars per gigabyte and pennies per IOPS
- HDDs are pennies per gigabyte and dollars per IOPS

- Prices sampled in early September 2012 and are subject to change.
- SSD pricing includes drive and PCIe card form factors.
- MLC pricing includes eMLC and cMLC.
- The HDD supply chain appears to have recovered from the Thailand flooding that occurred in the Fall of 2011. HDD availability and prices are beginning to return to pre-flood levels.
Storage Price History

Source: Dr. Ed Grochowski, Computer Storage Consultant, Flash Memory Summit 2012
Solid-State Storage Form Factors

- SSD-specific form factors
- Disk drive form factor
- PCI-Express (PCIe) card form factor
- DIMM form factor
Solid-State Storage Form Factors

SSD-Specific Form Factors

● mSATA
  - Introduced by the Serial ATA International Organization (SATA-IO) in 2009
  - Originally intended for small form factor HDDs and SSDs, but primarily used for SSDs
  - mSATA interface resembles mini-PCIe interface
  - Motherboards are beginning to appear with mSATA ports (or connectors) as of late 2011 and early 2012
  - Supports 1.5 Gb/s, 3.0 Gb/s and 6.0 Gb/s transfer rates
  - Physical dimensions shown in upcoming chart
Solid-State Storage Form Factors

SSD-Specific Form Factors

● μSSD
  - Introduced by SATA-IO in 2011
  - Uses a single ball grid array (BGA) package
    ▪ Can be surface mounted directly on a motherboard
    ▪ Not the same as traditional physical SATA interface
    ▪ SATA 6Gb/s
  - Intended for mobile platforms such as tablets and ultrabooks
  - Consumes less power than traditional SATA interface devices, as low as 10mW in slumber mode
### Solid-State Storage Form Factors

#### Disk Drive Form Factor

- SSDs are available in disk drive form factor
  - Most common – 2.5-inch
  - Varying heights or thickness
  - Slight variations depending on manufacturer

<table>
<thead>
<tr>
<th>Width (in/mm)</th>
<th>mSATA</th>
<th>1.8-inch</th>
<th>2.5-inch</th>
<th>3.5-inch</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Width (in/mm)</strong></td>
<td>1.18/30.0</td>
<td>2.13/54.0</td>
<td>2.76/70.1</td>
<td>4.0/101.6</td>
</tr>
<tr>
<td>Depth (in/mm)</td>
<td>2/50.8</td>
<td>3.1/78.74</td>
<td>3.955/100.45</td>
<td>5.76/146.52</td>
</tr>
<tr>
<td>Height (in/mm)</td>
<td>0.191/4.85</td>
<td>0.315/8.0</td>
<td>0.591/15.0</td>
<td>1.0/25.4</td>
</tr>
</tbody>
</table>

The traditional term for expressing the width of disk drives is not the actual measurement. For example, “3.5-inch” drives are actually 4 inches wide.
Solid-State Storage Form Factors

Disk Drive Form Factor

- **Interfaces**
  - **SATA II (3Gb/s) & III (6Gb/s)**
    - Available for most sizes
  - **SAS (6Gb/s)**
    - Primarily on 2.5-inch and 3.5-inch drives
  - **IDE/PATA for older SSDs**
  - **Some Fiber Channel (FC) for older enterprise SSDs**
    - Primarily 3.5-inch drives
  - **SCSI Express (2.5-inch PCIe)**
Solid-State Storage Form Factors

Disk Drive Form Factor

- 2.5-inch SSD varying thickness
- 3.5-inch SSD
- 3.5-inch HDD

Interfaces:
- SATA Interface (notch in middle)
- SAS Interface (no notch in middle)
Solid-State Storage Form Factors

Disk Drive Form Factor

- **SCSI Express (2.5-inch PCIe)**
  - Combines proven SCSI protocol with performance of PCIe bus
  - Products began shipping in 2012
  - Ideal for SSDs
### Solid-State Storage Form Factors

**PCI-Express (PCIe) Cards**

- PCI-Express specification history
  - Version 1.0a – 2003
  - Version 2.0 – 2007
  - Version 3.0 – 2010
- Measured in Gigatransfers per second (GT/s)
  - Bandwidth specified by indicating number of lanes such as “x1”, “x2”, etc., and generally spoken as “by 1”, “by 2”, etc.

<table>
<thead>
<tr>
<th></th>
<th>GT/s</th>
<th>Encoding</th>
<th>x1 (MB/s)</th>
<th>x2 (MB/s)</th>
<th>x4 (GB/s)</th>
<th>x8 (GB/s)</th>
<th>x16 (GB/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCIe 1.x</td>
<td>2.5</td>
<td>8b/10b</td>
<td>250</td>
<td>500</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>PCIe 2.x</td>
<td>5</td>
<td>8b/10b</td>
<td>500</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>PCIe 3.x</td>
<td>8</td>
<td>128b/130b</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>16</td>
</tr>
</tbody>
</table>

**March 6, 2012**

The major server vendors announced their PCIe 3.0 servers. These have up to 40 PCIe 3.0 lanes per processor (Intel Xeon E5-2600) socket.
Solid-State Storage Form Factors

PCI-Express (PCIe) Cards

- **Standard dimensions**
  - Height
    - Standard height – 4.2 inches (107mm)
    - Low profile – 2.5 inches (64 mm)
  - Length
    - Full length – 12.2 inches (312mm)
    - Half length – 6.6 inches (167mm)
  - Width
    - Single and double-width

- **Mini PCIe**
  - 30mm x 51mm or 30mm x 26.5mm
  - Provides 1 lane (x1) of PCIe
  - Some are compatible with the mSATA interface
Solid-State Storage Form Factors

PCI-Express (PCIe) Cards

- SSD Capacities
  - Full-size cards – Up to 5 TB (Fusion-io Octal: 5.12TB)
  - Mini PCIe – up to 256 GB

- Considerations
  - Make sure the PCIe SSD will physically fit inside the server
  - Some full-size PCIe SSDs require more power than the PCIe bus can provide
    - If the PCIe SSD needs additional power, make sure your server has extra power cables
Solid-State Storage Form Factors

NVM-Express (NVMe)

● Scalable host controller interface designed for enterprise and client SSDs
  - Targeted at “high-frequency” storage applications
  - Goal is to streamline access to SSD devices that are directly connected to the PCIe bus, including the storage stack in the O.S.
  - Compatible with SCSI/SAS, but uses a command set of six I/O commands for efficiency
● First enterprise products expected late 2012
● More information:
  - http://www.nvmexpress.org/
Solid-State Storage Form Factors

DIMM Form Factor

- DIMM – Dual in-line memory module
- SATADIMM
  - Uses a DDR3 240-pin DIMM form factor with flash storage and a SATA interface
    - Up to 480GB per DIMM socket
    - Gets power from the DIMM socket, data transfer via the SATA interface
  - Two implementation ideas
    - If you don’t fill all your DIMMs with memory, consider SSD
    - Build a storage appliance in a 1 rack unit (1U) server full of SATADIMM SSD
Solid-State Storage System Solutions

- Traditional disk arrays
- All-flash arrays
- Caching appliances
Solid-State Storage System Solutions

Traditional Disk Arrays

● Can use SSDs in place of HDDs in disk arrays
● These SSDs can be used for caching or tiering, or sometimes both
● Three storage tiers of devices are typically available
  - SSD
  - 15K and 10K low capacity drives
  - 7200RPM large capacity drives
● Typically SSD capacity is 3% - 10% of the HDD capacity
● Newer controllers are able to handle increased numbers of SSDs
Solid-State Storage System Solutions

All-Flash Arrays

● Use all SSDs – No HDDs
● Capacities up to 1 PB
  - Some have up to 48 TB in 2U & 1 PB in one rack
● Some have advanced features such as thin provisioning, compression, deduplication
● These are available today from several start-up companies – expect similar products from the big storage vendors in the future
  - Some start-ups may get acquired by larger vendors
Solid-State Storage System Solutions

Caching Appliances

- Use combination of DRAM and SSD
- The capacity is used for caching in front of existing SAN storage or NAS storage
## Power and Cooling Comparison – HDD vs. SSD

### Disk Drive Form Factor

<table>
<thead>
<tr>
<th>Device type</th>
<th>RPM</th>
<th>Form factor</th>
<th>Interface</th>
<th>Watts Typical</th>
<th>Watts Idle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spinning disk</td>
<td>15K</td>
<td>3.5”</td>
<td>FC/SAS</td>
<td>13 – 19</td>
<td>8 – 14</td>
</tr>
<tr>
<td>Spinning disk</td>
<td>15K</td>
<td>2.5”</td>
<td>SAS</td>
<td>8 – 14</td>
<td>5 – 7</td>
</tr>
<tr>
<td>Spinning disk</td>
<td>10K</td>
<td>3.5”</td>
<td>FC/SCSI</td>
<td>11 – 18</td>
<td>6 – 13</td>
</tr>
<tr>
<td>Spinning disk</td>
<td>10K</td>
<td>2.5”</td>
<td>SAS</td>
<td>8 – 14</td>
<td>3 – 6</td>
</tr>
<tr>
<td>Spinning disk</td>
<td>7.2K</td>
<td>3.5”</td>
<td>SAS/SATA</td>
<td>7 – 13</td>
<td>3 – 9</td>
</tr>
<tr>
<td>Spinning disk</td>
<td>7.2K/5.4K</td>
<td>2.5”</td>
<td>SATA</td>
<td>1 – 4</td>
<td>0.7 – 1</td>
</tr>
<tr>
<td>SSD: SLC-flash</td>
<td>-</td>
<td>*</td>
<td>SAS/SATA</td>
<td>1 – 8</td>
<td>0.05 – 4</td>
</tr>
<tr>
<td>SSD: MLC-flash</td>
<td>-</td>
<td>*</td>
<td>SAS/SATA</td>
<td>0.1 – 3</td>
<td>0.05 – 0.5</td>
</tr>
</tbody>
</table>

*Typically in data centers, every watt of power consumed by computing equipment requires another 0.5 – 1.0 watts of power to cool it.*

* SSDs are available in 3.5”, 2.5” and 1.8” drive form factors and other form factors
Operating System Behavior with NAND Flash

- Operating systems must treat flash SSDs differently
  - Trim – Notify the underlying device regarding data that is no longer needed
    - Trim is currently available for SATA interfaces only. The SAS committee has added UNMAP to the SAS/SCSI spec.
  - Windows 7 & 8 and Windows Server 2008 R2 & 2012
    - Defragmenting is off by default for flash SSDs
  - RHEL 6 with EXT4, but Trim is not enabled by default
  - Apple OS X Lion 10.7 for Apple-branded SSDs only

- For those operating systems that do not natively support Trim, SSD vendors provide separate applications
  - Example: Intel RapidStorage 9.6+
SSD Caching

- Caching controller identifies any frequently accessed data ("hot data") and automatically moves *a copy* of the hot data to SSD media.

- SSD impact
  - Multiple applications can benefit from the SSD cache simultaneously.
  - Performance improves over time, as cache is populated with data.
    - This is known as "cache warm-up" or "cache ramp-up".

- Some caching solutions cache only the reads, others cache both reads and writes.

- Overall HDD I/O load is reduced – Fewer I/Os.
SSD Caching Workloads

- **Cache Friendly Workloads**
  - Hot spots with repeated access
  - OLTP databases
  - Database indexes
  - File system table of contents (MFT, inodes, etc.)

- **Cache Un-friendly Workloads**
  - Data that is accessed approximately evenly and is larger than the cache
SSD Primary Storage and Tiering

- Data placement options for SSD
  - User decides what data to move and when to move it
  - Automation (tiering) software selects and moves data

- SSD impact
  - Benefits only the applications that use the data placed on the SSD
  - Performance improves instantly
Response Time Metrics

- Jakob Nielsen’s Alertbox, June 21, 2010
  - This study was conducted for web server applications, but these guidelines also apply to other applications

- Response-time limits
  - **0.1 seconds** – Gives the feeling of instantaneous response
  - **1 second** – Users’ flow of thought is seamless
  - **1-10 seconds** – Users feel at the mercy of the computer and wish it was faster
  - **10+ seconds** – Users start thinking about other things
SSD Performance Test Results

Two Sets Tests

1. SSD caching tests
2. SSD primary storage tests

- Full evaluation reports available in Demartek SSD Zone: www.demartek.com/SSD
  - More examples are available on our website

- Includes several SSD caching and primary storage validation tests.
Performance Issues

Bottlenecks and CPU Utilization

- SSD technology can move the bottleneck to unexpected places
  - In Demartek lab tests, the 1GbE network was the bottleneck during an initial PCIe card test, requiring us to go to the 10GbE network to get the full performance of the PCIe card

- SSD technology can drive up CPU utilization
  - Considerably more work can get done with SSD technology, which can significantly increase CPU utilization
SSD Caching Test 1 – O.S. & Web Content

Test Configuration

[Diagram showing the test configuration with details like Load Generator #1, Load Generator #2, Web Server, LSI MegaRAID 9280-8e, 6Gb/s SAS/SATA Controller, 6Gb/s SAS cables, 6x 500GB SATA disk drives, and 2x 32GB SATA SSD (SLC).]
SSD Caching Test 1 – O.S. & Web Content

Test Results – Total Hits

**Total Hits – CacheCade Software**

- **HDD only:** 1,285,708
- **1 SSD:** 4,241,171 (3.3 x HDD)
- **2 SSD:** 6,710,898 (5.2 x HDD)

Elapsed Time: 90 minutes
SSD Caching Test 1 – O.S. & Web Content

Test Results – Throughput

Throughput – CacheCade Software

Throughput

- HDD only
- 1 SSD
- 2 SSD

Megabits Per Second

Elapsed Time in Minutes

Throughput

- 416.551
  7.2 x HDD
- 211.231
  3.6 x HDD
- 58.136

0 10 20 30 40 50 60 70 80 90

0 50 100 150 200 250 300 350 400 450
SSD Caching Test 1 – O.S. & Web Content

Test Results – Average Page Response Time

Average Page Response Time – CacheCade Software
(Lower is better)

- HDD only: 0.1676 sec
- 1 SSD: 0.0429 sec (25.6% HDD)
- 2 SSD: 0.0190 sec (11.3% HDD)
- HDD: 0.1676 sec
SSD Caching Tests 2 & 3

Test Configuration (Tests 2 & 3)
SSD Caching Test 2 – Oracle OLTP Workload

Test Results – Transactions per Minute

VFCache – Oracle OLTP Database on VMAX
VMAX 4 engine, 64 x 15K rpm for data, 16 x 15K for log

VFCache enabled at 10 minutes into the test run

~ 3.3X
SSD Caching Test 2 – Oracle OLTP Workload

Test Results – Effect of Cache on Storage System I/O

VMAX: Total I/Os, Reads and Writes

I/O per Second

Time

Total

Reads

Writes
SSD Caching Test 3 – SQL Server OLTP Workload

Test Results – Transactions per Second

VFCache: SQL Server Database on VNX

VFCache enabled at 13 minutes into the test run

~ 3.6X
SSD Caching Test 3 – SQL Server OLTP Workload

Test Results – Physical Disk Statistics

**VFCache – Reads per Second (Physical Disk)**

**VFCache – Seconds per Read (Physical Disk)**
Performance Results – Demartek Testing

Primary Storage Tests

- Various primary storage test results, including:
  - Web server application comparison between PCIe card and two HDD configurations
- Results also compare electric power consumption
Performance Results – Demartek Testing

Test Configuration

LSI™ WarpDrive Acceleration Card Performance Evaluation in Access-Intensive Web Server Environments

- Load Generator #1
  - 10GbE connection
- 10GbE Switch
- Load Generator #2
  - 10GbE connection
- Web Server
  - 6Gbps SAS cables
- LSI 620J Disk Enclosure with
  - 24x 73GB 6Gbps SAS 15K RPM disk drives
- LSI WarpDrive PCIe Solid State Storage Card
- LSI SAS 9211-8i HBA
- LSI MegaRAID 9280-8e 6Gbps SAS/SATA Controller
Web Server Test

**Total Hits**

- **HDD-6**: 5,707,296
- **HDD-24**: 32,420,139
- **WarpDrive**: 104,816,357

Elapsed Time: 90 minutes

Comparative Performance:
- 18.37 x HDD-6
- 3.23 x HDD-24
Performance Results – Demartek Testing

Web Server Test

Throughput – 10GbE Connection

Average: 5429.2 Mbps
(3.2 x HDD-24)
(17.5 x HDD-6)

Averages exclude the first 10 minutes of the test run
Performance Results – Demartek Testing

Web Server Test

Average Page Response Time
(Lower is better)

WarpDrive: 0.0107 sec
3.1x faster than HDD-24
16.5x faster than HDD-6
Performance Results – Demartek Testing

Web Server Test

Web Server Power Consumption

- HDD-6
- HDD-24
- WarpDrive
- Server only, idle system

Web server load test running
Performance Results – Demartek Testing

Benefits

● Higher performance
● Lower power consumption
● Street price for the solution tested is about the same for the server plus either:
  - PCIe SSD
  - 24x 15K RPM drives, RAID controller, external disk shelf
● Smaller rack space
● Full report:  
Demartek Free Resources

- Demartek FC Zone
  - www.demartek.com/FC

- Demartek FCoE Zone
  - www.demartek.com/FCoE

- Demartek iSCSI Zone
  - www.demartek.com/iSCSI

- Demartek SSD Zone
  - www.demartek.com/SSD

- Demartek SSD Deployment Guide
Demartek Storage Interface Comparison

Demartek Storage Interface Comparison

Contents
- Acronyms
- Storage Networking Interface Comparison Table
- Transfer Rate, Bits vs. Bytes, and Encoding Schemes
- History
- Roadmaps
- Cables: Fiber Optics and Copper
- Connector Types
- PCI Express (PCIe)

- www.demartek.com/Demartek_Interface_Comparison.html
- Or search for “storage interface comparison”
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Contact Information

(303) 940-7575
www.demartek.com
http://twitter.com/Demartek
YouTube: www.youtube.com/Demartek
Skype: Demartek

Dennis Martin, President
dennis@demartek.com
www.linkedin.com/in/dennismartin