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Inventor(s) Lee; Hyun Yoo et al.

Asymmetric Read-Write Sequence for Interconnected Dies

Abstract

Apparatuses and techniques for implementing an asymmetric read-write sequence for interconnected dies are described. The asymmetric read-write sequence refers to an asymmetric die-access sequence for read versus write operations. The "asymmetric" term refers to a difference in an order in which data is written to or read from interface and linked dies of the interconnected die architecture. The orders for the read and write operations can be chosen such that a delay associated with transferring data between the interconnected dies occurs as data passes between the interface die and a memory controller. With asymmetric read-write burst sequences, overall timing of the read and write operations of a memory device may be impacted less, if at all, by a timing delay associated with the interconnected die architecture.

Inventors: **Lee; Hyun Yoo (Boise, ID), Kim; Kang-Yong (Boise, ID), McBride Brown; Jason (Austin, TX), Bringivijayaraghavan; Venkatraghavan (Hyderabad, IN), Vankayala; Vijayakrishna J. (Allen, TX)**

Applicant: **Micron Technology, Inc.** (Boise, ID)

Family ID: **89999797**

Assignee: **Micron Technology, Inc. (Boise, ID)**

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATION
[0001] This application claims the benefit of U.S. Non-Provisional patent application Ser. No. 17/823,443 filed on Aug. 30, 2022, the disclosure of which is incorporated by reference herein in its entirety.
BACKGROUND
[0002] A processor executes code based on data to run applications and provide features to a user. The processor obtains the code and the data from a memory that can store information. Thus, like a processor's speed or number of cores, a memory's characteristics can impact the performance of an electronic device. Different types of memory have different characteristics. Memory types include volatile memory and nonvolatile memory, such as random access memory (RAM) and flash memory, respectively. RAM can include static RAM (SRAM) and dynamic RAM (DRAM).
[0003] Demands on the different types of memory continue to evolve and grow. For example, as processors are engineered to execute code faster, such processors can benefit from accessing memories more quickly. Applications may also operate on ever-larger data sets that use ever-larger memories. Due to battery-powered electronic devices and power-hungry data centers, energy-usage constraints are becoming more prevalent for memory systems. Further, manufacturers may seek smaller memories as the form factors of portable electronic device continue to shrink. Accommodating these various demands is thus complicated by the diverse strengths and capabilities of different types of memories.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
[0004] Apparatuses of and techniques for using an asymmetric read-write sequence for interconnected dies are described with reference to the following drawings. The same numbers are used throughout the drawings to reference like features and components:
[0005] FIG. **1** illustrates an example operating environment including apparatuses that can implement an asymmetric read-write sequence for interconnected dies;
[0006] FIG. **2** illustrates an example computing system that can implement an asymmetric read-write sequence for interconnected dies;
[0007] FIG. **3** illustrates an example memory device in which an asymmetric read-write sequence for interconnected dies can be implemented;
[0008] FIG. **4** illustrates an example of a system that includes a host device and a memory device coupled together via an interconnect in which an asymmetric read-write sequence for interconnected dies may be implemented within the memory device;
[0009] FIG. **5** illustrates an example package with interconnected dies that can implement an asymmetric read-write sequence;
[0010] FIG. **6** illustrates example connections between a memory controller and multiple interconnected dies;
[0011] FIG. **7** illustrates an example timing diagram of a write operation in accordance with an asymmetric read-write sequence;
[0012] FIG. **8** illustrates an example timing diagram of a read operation in accordance with an

asymmetric read-write sequence;

[0013] FIG. **9** illustrates an example method for implementing an asymmetric read-write sequence for interconnected dies; and

[0014] FIG. **10** illustrates an example method for implementing an asymmetric read-write sequence for interconnected dies.

DETAILED DESCRIPTION

Overview

[0015] Computers, smartphones, and other electronic devices operate using processors and memories to run a variety of programs and applications, ranging from low-power operating systems and background utilities to computationally intensive applications for high-resolution graphics, computer simulations, artificial intelligence (AI), and so forth. Execution speeds associated with these programs and applications are often related to the performance of a memory of the electronic device, which is contingent, in part, on any delays associated with memory transfer.

[0016] A memory device may have an interconnected die architecture (e.g., a stacked or linked die architecture). This architecture uses at least one set of interconnected dies (or at least one set of interconnected dice), such as at least one interface die that is connected to at least one linked die within a combined package. The interface die can directly send data to or receive data from a memory controller. In contrast, the linked die indirectly sends data to or receives data from the memory controller through the interface die. Explained another way, the interface die acts as an interface and passes data between the linked die and the memory controller. The interface and linked dies may share joint access to an address bus. The interconnected die architecture can be relatively lower cost and/or occupy a smaller volume compared to other architectures with multiple dies. However, the interconnected die architecture can experience additional timing penalties associated with transferring data between the interface die and the linked die. Sometimes this timing penalty or timing delay can increase a time it takes the memory device to perform read or write operations.

[0017] To address this and other issues regarding an interconnected die architecture, this document describes aspects of an asymmetric-die-access sequence for read versus write operations. The "asymmetric" term refers to a difference in an order in which data is written to or read from the interface and linked dies of the interconnected die architecture. The orders for the read and write operations are chosen such that a delay associated with transferring data between the interconnected dies occurs as data passes between the interface die and a memory controller. With asymmetric read-write burst sequences, overall timing of the read and write operations of a memory device are impacted less, if at all, by a timing delay associated with the interconnected die architecture.

[0018] In some cases, the apparatuses and methods that are described herein may be appropriate for memory that is designed for lower power operations or that is targeted for energy-efficient applications. Thus, the described principles may be incorporated into a low-power memory device or a memory controller that communicates with such a low-power memory device. An example of a memory standard that relates to low-power applications is the Low-Power Double Data Rate (LPDDR) standard for synchronous DRAM (SDRAM) as promulgated by the Joint Electron Device Engineering Council (JEDEC) Solid State Technology Association. Some terminology in this document may draw from one or more of these standards or versions thereof, like the LPDDR5 standard, for clarity. The described principles, however, are also applicable to memories that comport with other standards, including other LPDDR standards (e.g., earlier versions or future versions like LPDDR6), and to memories that do not adhere to a public standard.

[0019] The density of memory devices continues to increase to maximize available memory and circuit area because improved communication protocols allow for higher rates of data transfer between processors and memory devices. An example of such an improved protocol is the Compute Express Link™ (CXL™) protocol or standard (referred to hereinafter as "the CXL

protocol" or "the CXL standard"). The CXL protocol can be implemented over a physical layer that is governed by, for instance, the PCIe® (Peripheral Component Interconnect Express) protocol. The CXL protocol targets intensive workloads for processors and memory devices (e.g., accelerators, memory expanders), where efficient, coherent memory access or interactions between processors and memory is advantageous.

[0020] The CXL protocol addresses some of the limitations of PCIe links by providing an interface that leverages, for example, the PCIe 5.0 physical layer and electricals, while providing lower-latency paths for memory access and coherent caching between processors and memory devices. It offers high-bandwidth, low-latency connectivity between host devices (e.g., processors, CPUs, SoCs) and memory devices (e.g., accelerators, memory expanders, memory buffers, smart input/output (I/O) devices). The CXL protocol also addresses growing high-performance computational workloads by supporting heterogeneous processing and memory systems with potential applications in artificial intelligence, machine learning, communication systems, and other high-performance computing.

[0021] An asymmetric read-write sequence may be used in CXL implementations. An example implementation, for instance, can include a memory device with multiple memory controllers and/or one or more sets of interconnected dies. Each set of interconnected dies includes at least one interface die that is connected to at least one linked die via an interconnect. The interface die can directly send data to or receive data from a memory controller. In contrast, the linked die indirectly sends data to or receives data from the memory controller through the interface die and the interconnect. Explained another way, the interface die acts as an interface and passes data between the linked die and the memory controller.

[0022] There can be additional timing delays associated with transferring data between the linked die and the memory controller. For example, writing data to or reading data from the linked die incurs a timing delay associated with transferring data across the interconnect between the interconnected dies. During write operations, a timing delay occurs as data is transferred from the interface die to the linked die. During read operations, a timing delay occurs as data is transferred from the linked die to the interface die.

[0023] The asymmetric read-write sequence, however, can mask these timing delays by performing write and read operations according to different sequences. A first sequence for write operations, for instance, causes a first chunk of a burst of write data to be written to the linked die, and causes a second chunk of the burst of write data to be written to the interface die. As such, the first sequence enables at least part of a timing delay associated with the transfer of the first chunk from the interface die to the linked die to occur during at least a portion of time that the interface die receives the second chunk from the memory controller.

[0024] A second sequence for read operations is different than the first sequence for write operations. The second sequence, for instance, causes a first chunk of a burst of read data to be read from the interface die, and causes a second chunk of the burst read data to be read from the linked die. As such, the second sequence enables at least part of a timing delay associated with the transfer of the second chunk from the linked die to the interface die to occur during at least a portion of time that the interface die transmits the first chunk of read data to the memory controller.

[0025] In aspects, an asymmetric read-write sequence may be used in situations where high-density memory is used, for example in CXL implementations. However, the asymmetric read-write sequence may be implemented in various other types of memory devices with interconnected dies to ensure overall timing of the read and write operations of a memory device are impacted less, if at all, by a timing delay associated with the interconnected die architecture.

Example Operating Environments

[0026] FIG. **1** illustrates, at **100** generally, an example operating environment including an apparatus **102** that can implement an asymmetric read-write sequence for interconnected dies. The apparatus **102** can include various types of electronic devices, including an internet-of-things (IoT)

device **102-1**, tablet device **102-2**, smartphone **102-3**, notebook computer **102-4**, passenger vehicle **102-5**, server computer **102-6**, and server cluster **102-7** that may be part of cloud computing infrastructure, a data center, or a portion thereof (e.g., a PCB). Other examples of the apparatus **102** include a wearable device (e.g., a smartwatch or intelligent glasses), entertainment device (e.g., a set-top box, video dongle, smart television, a gaming device), desktop computer, motherboard, server blade, consumer appliance, vehicle, drone, industrial equipment, security device, sensor, or the electronic components thereof. Each type of apparatus can include one or more components to provide computing functionalities or features.

[0027] In example implementations, the apparatus **102** can include at least one host device **104**, at least one interconnect **106**, and at least one memory device **108**. The host device **104** can include at least one processor **110**, at least one cache memory **112**, and a memory controller **114**. The memory device **108**, which can also be realized with a memory module, can include, for example, a dynamic random-access memory (DRAM) die or module (e.g., Low-Power Double Data Rate synchronous DRAM (LPDDR SDRAM)). The DRAM die or module can include a three-dimensional (3D) stacked DRAM device, which may be a high-bandwidth memory (HBM) device or a hybrid memory cube (HMC) device. The memory device **108** can operate as a main memory for the apparatus **102**. Although not illustrated, the apparatus **102** can also include storage memory. The storage memory can include, for example, a storage-class memory device (e.g., a flash memory, hard disk drive, solid-state drive, phase-change memory (PCM), or memory employing 3D XPoint™).

[0028] The processor **110** is operatively coupled to the cache memory **112**, which is operatively coupled to the memory controller **114**. The processor **110** is also coupled, directly or indirectly, to the memory controller **114**. The host device **104** may include other components to form, for instance, a system-on-a-chip (SoC). The processor **110** may include a general-purpose processor, central processing unit (CPU), graphics processing unit (GPU), neural network engine or accelerator, application-specific integrated circuit (ASIC), field-programmable gate array (FPGA) integrated circuit (IC), or communications processor (e.g., a modem or baseband processor).

[0029] In operation, the memory controller **114** can provide a high-level or logical interface between the processor **110** and at least one memory (e.g., an external memory). The memory controller **114** may be realized with any of a variety of suitable memory controllers (e.g., a DDR memory controller that can process requests for data stored on the memory device **108**). Although not shown, the host device **104** may include a physical interface (PHY) that transfers data between the memory controller **114** and the memory device **108** through the interconnect **106**. For example, the physical interface may be an interface that is compatible with a DDR PHY Interface (DFI) Group interface protocol. The memory controller **114** can, for example, receive memory requests from the processor **110** and provide the memory requests to external memory with appropriate formatting, timing, and reordering. The memory controller **114** can also forward to the processor **110** responses to the memory requests received from external memory.

[0030] The host device **104** is operatively coupled, via the interconnect **106**, to the memory device **108**. In some examples, the memory device **108** is connected to the host device **104** via the interconnect **106** with an intervening buffer or cache. The memory device **108** may operatively couple to storage memory (not shown). The host device **104** can also be coupled, directly or indirectly via the interconnect **106**, to the memory device **108** and the storage memory. The interconnect **106** and other interconnects (not illustrated in FIG. **1**) can transfer data between two or more components of the apparatus **102**. Examples of the interconnect **106** include a bus, switching fabric, or one or more wires that carry voltage or current signals.

[0031] In some implementations, the interconnect **106** can include at least one command and address bus **116** (CA bus **116**) and at least one data bus **118** (DQ bus **118**). Each bus may be a unidirectional or a bidirectional bus. The CA bus **116** and the DQ bus **118** may couple to CA and DQ pins, respectively, of the memory device **108**. The interconnect **106** may also include a chip-

select (CS) I/O or line (not illustrated in FIG. **1**) that can, for example, couple to one or more CS pins of the memory device **108**. The interconnect **106** may further include a clock bus (CK bus—not illustrated in FIG. **1**) that is part of or separate from the CA bus **122**.

[0032] In other implementations, the interconnect **106** can be realized as a CXL link. In other words, the interconnect **106** can comport with at least one CXL standard or protocol. The CXL link can provide an interface on top of the physical layer and electricals of a PCIe 5.0 physical layer. The CXL link can cause requests to and responses from the memory device **108** to be packaged as flits. An example implementation of the apparatus **102** with a CXL link is discussed in greater detail with respect to FIG. **4**. In still other implementations, the interconnect **106** can be another type of link, including a PCIe 5.0 link. In this document, some terminology may draw from one or more of these standards or versions thereof, like the CXL standard, for clarity. The described principles, however, are also applicable to memories and systems that comport with other standards and types of interconnects.

[0033] The illustrated components of the apparatus **102** represent an example architecture with a hierarchical memory system. A hierarchical memory system may include memories at different levels, with each level having memory with a different speed or capacity. As illustrated, the cache memory **112** logically couples the processor **110** to the memory device **108**. In the illustrated implementation, the cache memory **112** is at a higher level than the memory device **108**. A storage memory, in turn, can be at a lower level than the main memory (e.g., the memory device **108**). Memory at lower hierarchical levels may have a decreased speed but increased capacity relative to memory at higher hierarchical levels.

[0034] The apparatus **102** can be implemented in various manners with more, fewer, or different components. For example, the host device **104** may include multiple cache memories (e.g., including multiple levels of cache memory) or no cache memory. In other implementations, the host device **104** may omit the processor **110** or the memory controller **114**. A memory (e.g., the memory device **108**) may have an "internal" or "local" cache memory. As another example, the apparatus **102** may include cache memory between the interconnect **106** and the memory device **108**. Computer engineers can also include any of the illustrated components in distributed or shared memory systems.

[0035] Computer engineers may implement the host device **104** and the various memories in multiple manners. In some cases, the host device **104** and the memory device **108** can be disposed on, or physically supported by, a PCB (e.g., a rigid or flexible motherboard). The host device **104** and the memory device **108** may additionally be integrated together on an IC or fabricated on separate ICs and packaged together. The memory device **108** may also be coupled to multiple host devices **104** via one or more interconnects **106** and may respond to memory requests from two or more host devices **104**. Each host device **104** may include a respective memory controller **114**, or the multiple host devices **104** may share a memory controller **114**. This document describes with reference to FIG. **2** an example computing system architecture having at least one host device **104** coupled to a memory device **108**.

[0036] Two or more memory components (e.g., modules, dies, banks, or bank groups) can share the electrical paths or couplings of the interconnect **106**. In some implementations, the CA bus **116** transmits addresses and commands from the memory controller **114** of the host device **104** to the memory device **108**, which may exclude propagation of data. The DQ bus **118** can propagate data between the memory controller **114** and the memory device **108**. The memory device **108** may also be implemented as any suitable memory including, but not limited to, DRAM, SDRAM, three-dimensional (3D) stacked DRAM, DDR memory, or LPDDR memory (e.g., LPDDR DRAM or LPDDR SDRAM).

[0037] The memory device **108** can form at least part of the main memory of the apparatus **102**. The memory device **108** may, however, form at least part of a cache memory, a storage memory, or an SoC of the apparatus **102**. In some implementations, and as discussed in greater detail with

respect to FIG. **3**, at least a portion of the memory device **108** has an interconnected die architecture (e.g., a stacked die architecture or linked die architecture) with at least two interconnected dies **120**. The interconnected die architecture enables the memory device **108** to use two or more interconnected dies **120** for a single write or read access along a shared data path, which can be controlled or managed by a die of the interconnected dies **120**.

[0038] The interconnected dies **120** operate jointly to handle write and read requests issued by the memory controller **114** or another memory controller within the memory device **108**, depending on implementation. The interconnected dies **120** are further described with respect to FIGS. **5** and **6**.

[0039] FIG. **2** illustrates an example computing system **200** that can implement aspects of an asymmetric read-write sequence for interconnected dies **120**. In some implementations, the computing system **200** includes at least one memory device **108**, at least one interconnect **106**, and at least one processor **202**.

[0040] The memory device **108** can include, or be associated with, at least one memory array **204**, at least one interface **206**, and control circuitry **208** operatively coupled to the memory array **204**. The memory device **108** can correspond to one or more of the cache memory, the main memory, or a storage memory of the apparatus **102** of FIG. **1**. Thus, the memory array **204** can include an array of memory cells, including but not limited to memory cells of DRAM, SDRAM, 3D-stacked DRAM, DDR memory, low-power DRAM, or LPDDR SDRAM. For example, the memory array **204** can include memory cells of SDRAM configured as a memory module with one channel containing either 16 or 8 data (DQ) signals, double-data-rate input/output (I/O) signaling, and supporting a supply voltage of 0.3 to 0.5V. The density of the memory device **108** can range, for instance, from 2Gb to 32Gb.

[0041] The memory array **204** and the control circuitry **208** may be components on a single semiconductor die or on separate semiconductor dies. The memory array **204** or the control circuitry **208** may also be distributed across multiple dies, such as the interconnected dies **120**. Although not explicitly shown in FIG. **2**, the control circuitry **208** may include circuitry enabling one interconnected die to communicate with another interconnected die. This control circuitry may manage traffic on a bus that is separate from the interconnect **106**.

[0042] The control circuitry **208** can include various components that the memory device **108** can use to perform various operations. These operations can include communicating with other devices, managing memory performance, performing refresh operations (e.g., self-refresh operations or auto-refresh operations), and performing memory read or write operations. For example, the control circuitry **208** can include one or more registers **210**, at least one instance of array control logic **212**, and clock circuitry **214**. The registers **210** may be implemented, for example, as one or more registers that can store information to be used by the control circuitry **208** or another part of the memory device **108**. The array control logic **212** can include circuitry that provides command decoding, address decoding, input/output functions, amplification circuitry, power supply management, power control modes, and other functions. The clock circuitry **214** can synchronize various memory components with one or more external clock signals provided over the interconnect **106**, including a command/address clock or a data clock. The clock circuitry **214** can also use an internal clock signal to synchronize memory components and may provide timer functionality.

[0043] The interface **206** can couple the control circuitry **208** or the memory array **204** directly or indirectly to the interconnect **106**. As shown in FIG. **2**, the registers **210**, the array control logic **212**, and the clock circuitry **214** can be part of a single component (e.g., the control circuitry **208**). In other implementations, one or more of the registers **210**, the array control logic **212**, or the clock circuitry **214** may be separate components on a single semiconductor die or distributed across multiple semiconductor dies. These components may individually or jointly couple to the interconnect **106** via the interface **206**.

[0044] The interconnect **106** may use one or more of a variety of interconnects that

communicatively couple together various components and enable commands, addresses, or other information and data to be transferred between two or more components (e.g., between the memory device **108** and the processor **202**). Although the interconnect **106** is illustrated with a single line in FIG. **2**, the interconnect **106** may include at least one bus, at least one switching fabric, one or more wires or traces that carry voltage or current signals, at least one switch, one or more buffers, and so forth. Further, the interconnect **106** may be separated into at least a CA bus **116** and a DQ bus **118** (as illustrated in FIG. **1**). As discussed above with respect to FIG. **1**, the interconnect **106** can include a CXL link or comport with at least one CXL standard. The CXL link can provide an interface or overlay on top of the physical layer and electricals of the PCIe 5.0 physical layer.

[0045] In some aspects, the memory device **108** may be a "separate" component relative to the host device **104** (of FIG. **1**) or any of the processors **202**. The separate components can include a PCB, memory card, memory stick, and memory module (e.g., a single in-line memory module (SIMM) or dual in-line memory module (DIMM)). Thus, separate physical components may be located together within the same housing of an electronic device or may be distributed over a server rack, a data center, and so forth. Alternatively, the memory device **108** may be integrated with other physical components, including the host device **104** or the processor **202**, by being combined on a PCB or in a single package or an SoC.

[0046] As shown in FIG. **2**, the processors **202** may include a computer processor **202-1**, a baseband processor **202-2**, and an application processor **202-3**, coupled to the memory device **108** through the interconnect **106**. The processors **202** may include or form a part of a CPU, GPU, SoC, ASIC, or FPGA. In some cases, a single processor can comprise multiple processing resources, each dedicated to different functions (e.g., modem management, applications, graphics, central processing). In some implementations, the baseband processor **202-2** may include or be coupled to a modem (not illustrated in FIG. **2**) and referred to as a modem processor. The modem or the baseband processor **202-2** may be coupled wirelessly to a network via, for example, cellular, Wi-Fi®, Bluetooth®, near field, or another technology or protocol for wireless communication.

[0047] In some implementations, the processors **202** may be connected directly to the memory device **108** (e.g., via the interconnect **106**). In other implementations, one or more of the processors **202** may be indirectly connected to the memory device **108** (e.g., over a network connection or through one or more other devices). Further, the processor **202** may be realized as one that can communicate over a CXL-compatible interconnect. Accordingly, a respective processor **202** can include or be associated with a respective link controller, like the link controller **402** illustrated in FIG. **4**. Alternatively, two or more processors **202** may access the memory device **108** using a shared link controller **402**. In some of such cases, the memory device **108** may be implemented as a CXL-compatible memory device (e.g., as a CXL Type **3** memory expander) or another memory device that is compatible with a CXL protocol may also or instead be coupled to the interconnect **106**.

Example Techniques and Hardware

[0048] FIG. **3** illustrates an example memory device **108** in which an asymmetric read-write sequence for interconnected dies can be implemented. An example memory module **302** includes multiple dies **304**. As illustrated, the memory module **302** includes a first die **304-1**, a second die **304-2**, a third die **304-3**, and a Dth die **304**-D, with D representing a positive integer. Two or more of the dies **304-1** to **304**-D can be implemented as interconnected dies **120**. For example, the dies **304-1** and **304-2** can be interconnected dies **120**. In some cases, the memory module **302** includes multiple sets of interconnected dies **120**, such as multiple pairs of interconnected dies, or includes a set of interconnected dies **120** that has four or more dies.

[0049] As a few examples, the memory module **302** can be a SIMM or a DIMM. As another example, the memory module **302** can interface with other components via a bus interconnect (e.g., a Peripheral Component Interconnect Express (PCIe®) bus). The memory device **108** illustrated in FIGS. **1** and **2** can correspond, for example, to multiple dies (or dice) **304-1** through **304**-D, or a

memory module **302** with two or more dies **304**. As shown, the memory module **302** can include one or more electrical contacts **306** (e.g., pins) to interface the memory module **302** to other components.

[0050] The memory module **302** can be implemented in various manners. For example, the memory module **302** may include a PCB, and the multiple dies **304**-1 through **304**-D may be mounted or otherwise attached to the PCB. The dies **304** (e.g., memory dies) may be arranged in a line or along two or more dimensions (e.g., forming a grid or array). The dies **304** may have a similar size or may have different sizes. Each die **304** may be similar to another die **304** or different in size, shape, data capacity, or control circuitries. The dies **304** may also be positioned on a single side or on multiple sides of the memory module **302**. In some cases, the memory module **302** may be part of a CXL memory system or module.

[0051] FIG. **4** illustrates an example of a system **400** that includes a host device **104** and a memory device **108** that are coupled together via an interconnect **106**. The system **400** may form at least part of an apparatus **102** as shown in FIG. **1**. As illustrated, the host device **104** includes a processor **110** and a link controller **402**, which can be realized with at least one initiator **404**. Thus, the initiator **404** can be coupled to the processor **110** or to the interconnect **106** (including to both), and the initiator **404** can be coupled between the processor **110** and the interconnect **106**. Examples of initiators **404** may include a leader, a primary, a master, a main component, and so forth.

[0052] In the illustrated example system **400**, the memory device **108** includes a link controller **406**, which may be realized with at least one target **408**. The target **408** can be coupled to the interconnect **106**. Thus, the target **408** and the initiator **404** can be coupled to each other via the interconnect **106**. Example targets **408** may include a follower, a secondary, a slave, a responding component, and so forth. The memory device **108** also includes a memory, which may be realized with at least one memory module **302** or other component, such as a DRAM **410**, as is described further below.

[0053] In example implementations, the initiator **404** includes the link controller **402**, and the target **408** includes the link controller **406**. The link controller **402** or the link controller **406** can instigate, coordinate, cause, or otherwise control signaling across a physical or logical link realized by the interconnect **106** in accordance with one or more protocols. The link controller **402** may be coupled to the interconnect **106**. The link controller **406** may also be coupled to the interconnect **106**. Thus, the link controller **402** can be coupled to the link controller **406** via the interconnect **106**. Each link controller **402** or **406** may, for instance, control communications over the interconnect **106** at a link layer or at one or more other layers of a given protocol. Communication signaling may include, for example, a request **412** (e.g., a write request or a read request), a response **414** (e.g., a write response or a read response), and so forth.

[0054] The memory device **108** may further include at least one interconnect **416** and at least one memory controller **418** (e.g., MC **418**-1 and MC **418**-2). Within the memory device **108**, and relative to the target **408**, the interconnect **416**, the memory controller **418**, and/or the DRAM **410** (or other memory component) may be referred to as a "backend" component of the memory device **108**. In some cases, the interconnect **416** is internal to the memory device **108** and may operate in a manner the same as or different from the interconnect **106**.

[0055] As shown, the memory device **108** may include multiple memory controllers **418-1** and **418-2** and/or multiple DRAMs **410-1** and **410-2**. Although two each are shown, the memory device **108** may include one or more memory controllers **418** and/or one or more DRAMs **410**. For example, a memory device **108** may include four memory controllers **418** and sixteen DRAMs **410**, such as four DRAMs **410** per memory controller **418**. The memory components of the memory device **108** are depicted as DRAM **410** only as an example, for one or more of the memory components may be implemented as another type of memory. For instance, the memory components may include nonvolatile memory like flash or PCM. Alternatively, the memory components may include other types of volatile memory like static random-access memory

(SRAM). A memory device **108** may also include any combination of memory types. In example implementations, the DRAM **410-1** and/or the DRAM **410-2** include interconnected dies **120**.

[0056] In some cases, the memory device **108** may include the target **408**, the interconnect **416**, the at least one memory controller **418**, and the at least one DRAM **410** within a single housing or other enclosure. The enclosure, however, may be omitted or may be merged with an enclosure for the host device **104**, the system **400**, or an apparatus **102** (of FIG. **1**). The interconnect **416** can be disposed on a PCB. Each of the target **408**, the memory controller **418**, and the DRAM **410** may be fabricated on at least one IC and packaged together or separately. The packaged ICs may be secured to or otherwise supported by the PCB and may be directly or indirectly coupled to the interconnect **416**. In other cases, the target **408**, the interconnect **416**, and the one or more memory controllers **418** may be integrated together into one IC. In some of such cases, this IC may be coupled to a PCB, and one or more modules for the memory components (e.g., for the DRAM **410**) may also be coupled to the same PCB, which can form a CXL type of memory device **108**. This memory device **108** may be enclosed within a housing or may include such a housing. The components of the memory device **108** may, however, be fabricated, packaged, combined, and/or housed in other manners.

[0057] As illustrated in FIG. **4**, the target **408**, including the link controller **406** thereof, can be coupled to the interconnect **416**. Each memory controller **418** of the multiple memory controllers **418-1** and **418-2** can also be coupled to the interconnect **416**. Accordingly, the target **408** and each memory controller **418** of the multiple memory controllers **418-1** and **418-2** can communicate with each other via the interconnect **416**. Each memory controller **418** is coupled to at least one DRAM **410**. As shown, each respective memory controller **418** of the multiple memory controllers **418-1** and **418-2** is coupled to at least one respective DRAM **410** of the multiple DRAMs **410-1** and **410-2**. Each memory controller **418** of the multiple memory controllers **418-1** and **418-2** may, however, be coupled to a respective set of multiple DRAMs **410** (e.g., five DRAMs **410**) or other memory components.

[0058] Each memory controller **418** can access at least one DRAM **410** by implementing one or more memory access protocols to facilitate reading or writing data based on at least one memory address. The memory controller **418** can increase bandwidth or reduce latency for the memory accessing based on the memory type or organization of the memory components, like the DRAMs **410**. The multiple memory controllers **418-1** and **418-2** and the multiple DRAMs **410-1** and **410-2** can be organized in many different manners. For example, each memory controller **418** can realize one or more memory channels for accessing the DRAMs **410**. Further, the DRAMs **410** can be manufactured to include one or more ranks, such as a single-rank or a dual-rank memory module. Each DRAM **410** (e.g., at least one DRAM IC chip) may also include multiple banks, such as 8 or 16 banks.

[0059] This document now describes examples of the host device **104** accessing the memory device **108**. The examples are described in terms of a general access which may include a memory read access (e.g., a retrieval operation) or a memory write access (e.g., a storage operation). The processor **110** can provide a memory access request **420** to the initiator **404**. The memory access request **420** may be propagated over a bus or other interconnect that is internal to the host device **104**. This memory access request **420** may be or may include a read request or a write request. The initiator **404**, such as the link controller **402** thereof, can reformulate the memory access request **420** into a format that is suitable for the interconnect **106**. This formulation may be performed based on a physical protocol or a logical protocol (including both) applicable to the interconnect **106**. Examples of such protocols are described below.

[0060] The initiator **404** can thus prepare a request **412** and transmit the request **412** over the interconnect **106** to the target **408**. The target **408** receives the request **412** from the initiator **404** via the interconnect **106**. The target **408**, including the link controller **406** thereof, can process the request **412** to determine (e.g., extract or decode) the memory access request **420**. Based on the

determined memory access request **420**, the target **408** can forward a memory request **422** over the interconnect **416** to a memory controller **418**, which is the first memory controller **418-1** in this example. For other memory accesses, the targeted data may be accessed with the second DRAM **410-2** through the second memory controller **418-2**.

[0061] The first memory controller **418-1** can prepare a memory command **424** based on the memory request **422**. The first memory controller **418-1** can provide the memory command **424** to the first DRAM **410-1** over an interface or interconnect appropriate for the type of DRAM or other memory component. The first DRAM **410-1** receives the memory command **424** from the first memory controller **418-1** and can perform the corresponding memory operation. The memory command **424**, and corresponding memory operation, may pertain to a read operation, a write operation, a refresh operation, and so forth. Based on the results of the memory operation, the first DRAM **410-1** can generate a memory response **426**. If the memory request **422** is for a read operation, the memory response **426** can include the requested data. If the memory request **422** is for a write operation, the memory response **426** can include an acknowledgment that the write operation was performed successfully. The first DRAM **410-1** can return the memory response **426** to the first memory controller **418-1**.

[0062] The first memory controller **418-1** receives the memory response **426** from the first DRAM **410-1**. Based on the memory response **426**, the first memory controller **418-1** can prepare a memory response **428** and transmit the memory response **428** to the target **408** via the interconnect **416**. The target **408** receives the memory response **428** from the first memory controller **418-1** via the interconnect **416**. Based on this memory response **428**, and responsive to the corresponding request **412**, the target **408** can formulate a response **430** for the requested memory operation. The response **430** can include read data or a write acknowledgment and be formulated in accordance with one or more protocols of the interconnect **106**.

[0063] To respond to the request **412** from the host device **104**, the target **408** can transmit the response **430** to the initiator **404** over the interconnect **106**. Thus, the initiator **404** receives the response **430** from the target **408** via the interconnect **106**. The initiator **404** can therefore respond to the "originating" memory access request **420**, which is from the processor **110** in this example. To do so, the initiator **404** prepares a memory access response **432** using the information from the response **430** and provides the memory access response **432** to the processor **110**. In this way, the host device **104** can obtain memory access services from the memory device **108** using the interconnect **106**. Example aspects of an interconnect **106** are described next.

[0064] The interconnect **106** can be implemented in a myriad of manners to enable memory-related communications to be exchanged between the initiator **404** and the target **408**. Generally, the interconnect **106** can carry memory-related information, such as data or a memory address, between the initiator **404** and the target **408**. In some cases, the initiator **404** or the target **408** (including both) can prepare memory-related information for communication across the interconnect **106** by encapsulating such information. The memory-related information can be encapsulated into, for example, at least one packet (e.g., a flit). One or more packets may include headers with information indicating or describing the content of each packet.

[0065] In example implementations, the interconnect **106** can support, enforce, or enable memory coherency for a shared memory system, for a cache memory, for combinations thereof, and so forth. Additionally or alternatively, the interconnect **106** can be operated based on a credit allocation system. Possession of a credit can enable an entity, such as the initiator **404**, to transmit another memory request **412** to the target **408**. The target **408** may return credits to "refill" a credit balance at the initiator **404**. A credit-based communication scheme across the interconnect **106** may be implemented by credit logic of the target **408** or by credit logic of the initiator **404** (including by both working together in tandem).

[0066] The system **400**, the initiator **404** of the host device **104**, or the target **408** of the memory device **108** may operate or interface with the interconnect **106** in accordance with one or more

physical or logical protocols. For example, the interconnect **106** may be built in accordance with a Peripheral Component Interconnect Express (PCIe or PCI-e) standard. Applicable versions of the PCIe standard may include 1.x, 2.x, 3.x, 4.0, 5.0, 6.0, and future or alternative versions. In some cases, at least one other standard is layered over the physical-oriented PCIe standard. For example, the initiator **404** or the target **408** can communicate over the interconnect **106** in accordance with a Compute Express Link (CXL) standard. Applicable versions of the CXL standard may include 1.x, 2.0, and future or alternative versions. The CXL standard may operate based on credits, such as read credits and write credits. In such implementations, the link controller **402** and the link controller **406** can be CXL controllers.

[0067] Examples of an asymmetric read-write sequence are described herein with reference to at least one memory controller **114** or **418** and at least one memory device **108** (e.g., having a memory array **204**, a memory module **302**, and/or a DRAM **410**), including interconnected dies **120** thereof. The interconnected dies **120** are further described with respect to FIGS. **5** and **6**.

[0068] FIG. **5** illustrates an example package **500** with interconnected dies **120** that can implement an asymmetric read-write sequence. Although not shown, the package **500** can also include other components, such as one or more other components of the memory device **108** and/or one or more components of the host device **104**. In the depicted configuration, the package **500** includes a substrate **502**. The interconnected dies **120** are disposed on or embedded in the substrate **502**. The interconnected dies **120** include at least one interface die **504** and at least one linked die **506**. In this example, the package **500** is shown to include interface dies **504-1** to **504**-N and linked dies **506-1** to **506**-N, where N represents a positive integer. Each linked die **506** is coupled to an interface die **504** via an interconnect **508**. In FIG. **5**, the linked dies **506-1** to **506**-N are respectively coupled to the interface dies **504-1** to **504**-N by the interconnects **508-1** to **508**-N.

[0069] Although not explicitly shown, the interface die **504** is operatively coupled to the memory controller **114** or **418** (e.g., of FIG. **1** or **4**) and acts as an interface between the linked die **506** and the memory controller **114** or **418** for at least data transfers or exchanges. Although the interface die **504** and the linked die **506** can behave differently, the interface die **504** and the linked die **506** can be manufactured as a same type of die that includes the same circuit components. Once the package **500** is assembled, each of the dies can be programmed to function as an interface die **504** or a linked die **506**. As an example, the interconnected dies **120** can be programmed by setting at least one respective fuse in each die.

[0070] In example aspects, a set of interconnected dies **510** can refer to one interface die **504** and one linked die **506**. However, other configurations are also possible in which an interface die **504** is operatively coupled to two or more linked dies **506**. In general, the set of interconnected dies **510** refers to a group of interconnected dies **120** that are operatively coupled together. For example, the linked die **506** within the set of interconnected dies **510** is operatively coupled, via the interconnect **508**, to the interface die **504** within the set of interconnected dies **510**. Also, the interface die **504** within the set of interconnected dies **510** is operatively coupled, via the interconnect **508**, to one or more linked dies **506** within the set of interconnected dies **510**. In FIG. **5**, the interface die **504-1** and the linked die **506-1** can represent a first set of interconnected dies **510**, and the interface die **504**-N and the linked die **506**-N can represent an Nth set of interconnected dies **510**.

[0071] The interconnects **508-1** to **508**-N can transfer data between corresponding interface dies **504-1** to **504**-N and linked dies **506-1** to **506**-N, respectively. For example, the interconnect **508-1** can transfer data between the interface die **504-1** and the linked die **506-1**. Likewise, the interconnect **508**-N can transfer data between the interface die **504**-N and the linked die **506**-N. In an example implementation, the interconnects **508** support the transfer of 128 bits (e.g., 16 bytes) per access. Although the interconnects **508-1** to **508**-N are illustrated with individual lines in FIG. **5**, each interconnect **508** can include at least one bus, at least one switching fabric, one or more wires or traces that carry voltage or current signals, at least one switch, one or more buffers, and so forth.

[0072] The interface die **504** and/or the linked die **506** can each include at least one memory array **204**, at least one interface **206**, and control circuitry **208**. The interface **206** can couple the control circuitry **208** or the memory array **204** directly or indirectly to the interconnect **508**. The interface **206** can also include a data bus **512**. Examples for the pins of the interface die **504** and the linked die **506** are further described with respect to FIG. **6**.

[0073] FIG. **6** illustrates example connections between the memory controller **114** or **418** and multiple interconnected dies **120** of the memory device **108**. In the case of the memory controller **114**, the interconnect **106** can provide multiple lines of electrical communication between the memory controller **114** and each die of the interconnected dies **120**. Alternatively, in the case of the memory controller **418**, an interconnect **602** can provide multiple lines of electrical communication between the memory controller **418** and each die of the interconnected dies **120**. The lines of the interconnect **106** or **602** may correspond to clock (CK) lines, write clock (WCK) lines, write mask lines, command/address lines, or other memory communication lines. With the interconnect **106** or **602**, the interface die **504** and the linked die **506** can receive commands from a common command and address bus.

[0074] The interface die **504** and the linked die **506** each include a data pin **604** and a connected data pin **606**. The data pin **604** can represent multiple pins that enable the transfer of multiple bits per access. For example, the data pin **604** can represent eight pins. The data pin **604** may comport, at least partially, with LPDDR5, to another standard, or to no public standard. The interface die **504** and the linked die **506** differ in that the data pin **604** of the interface die **504** is active and operatively coupled to the memory controller **114** or **418**. In this way, the interface die **504** can "directly" transmit data to or "directly" receive data from the memory controller **114** or **418** without using another die as an intermediary for sending data to the memory controller **114** or **418** or receiving data from the memory controller **114** or **418**. In contrast, the data pin **604** of the linked die **506** is inactive and not operatively coupled to the memory controller **114** or **418**. As such, the linked die **506** is unable to directly communicate with the memory controller **114** or **418**. In particular, the linked die **506** is unable to directly transmit data to or directly receive data from the memory controller **114** or **418**. Instead, the linked die **506** can "indirectly" communicate with the memory controller **114** or **418** via at least one other die—the interface die **504**, which is described next.

[0075] The interface die **504** and the linked die **506** each include a connected data pin **606** (CQ **606**). The connected data pin **606** can represent multiple pins that enable the transfer of multiple bits per access. For example, the connected data pin **606** can represent 32 pins. The interconnect **508** operatively couples the linked die **506** to the interface die **504** via the connected data pin **606** of each die. With the interconnect **508** and the connected data pins **606**, the linked die **506** can transmit data to or receive data from the interface die **504**. The interface die **504** can transfer data from the memory controller **114** or **118** to the linked die **506**. Also, the interface die **504** can transfer data from the linked die **506** to the memory controller **114** or **118**. In this way, the linked die **506** can indirectly transmit data to or indirectly receive data from the memory controller **114** or **418** through the interface die **504**. Explained another way, the interface die **504** acts as an interface for the linked die **506** and passes data between the linked die **506** and the memory controller **114** or **418**.

[0076] The interconnected die architecture illustrated in FIG. **6** can reduce cost and conserve space within the apparatus **102**. For example, the interconnect **106** or **602** can be implemented with fewer lines of electrical communication as fewer pins on the linked die **506** may be active relative to the interface die **504**. These benefits may come at the cost of a timing penalty associated with transferring data between the interface die **504** and the linked die **506** via the interconnect **508**. Techniques for implementing an asymmetric read-write sequence, however, can enable overall timing of read and write operations to be impacted less, if at all, by such a timing penalty. Examples of the asymmetric read-write sequence is further described with respect to FIGS. **7** and **8**.

[0077] FIG. **7** illustrates an example timing diagram **700** of a write operation in accordance with an asymmetric read-write sequence. In FIG. **7**, time progresses from left to right. During a write operation, the interface die **504** receives, from the memory controller **114** or **418**, bursts of write data **702** at the data pin **604**. In this example, the bursts of write data **702** include a first burst of write data **702-1** and a second burst of write data **702-2**. Each burst of write data **702** includes multiple chunks **704**. For instance, the first burst of write data **702-1** includes a first chunk **704-1** and a second chunk **704-2**. The second burst of write data **702-2** includes a third chunk **704-3** and a fourth chunk **704-4**.

[0078] Each burst of write data **702** can include, for instance, 32 bytes in accordance with a mode of the memory device **108**. In example implementations, the first chunk **704-1** can correspond to a lower 16 bytes, and the second chunk **704-2** can correspond to an upper 16 bytes. In other words, the first chunk **704-1** can include a least-significant byte **706** (LSB **706**), and the second chunk **704-2** can include a most-significant byte **708** (MSB **708**). In total, the first chunk **704-1** and the second chunk **704-2** represent the 32 bytes of the first burst of write data **702-1**. Similarly, the third chunk **704-3** can represent a lower 16 bytes, and the fourth chunk **704-4** can represent an upper 16 bytes of the second burst of write data **702-2**. Bursts of write data **702** can, however, be of different lengths, such as 16 bytes. In this case, each chunk **704** can represent 8 bytes of the burst of write data **702**.

[0079] In some implementations, as each chunk **704** is received, the interface die **504** passes the chunk **704** through a deserializer **710** of the interface die **504**. The deserializer **710** can be implemented as part of the control circuitry **208**. In general, the deserializer **710** operates in a pipelined fashion on a previously received chunk **704** as a next chunk **704** is received at the data pin **604** of the interface die **504**. For example, the deserializer **710** operates on the first chunk **704-1** as the interface die **504** receives the second chunk **704-2** from the memory controller **114** or **418**.

[0080] After deserialization, the interface die **504** passes the chunk **704** to a data bus **512** of the linked die **506** or a data bus **512** of the interface die **504** in accordance with a first sequence **712**. The data buses **512** can be implemented, for instance, as part of the respective interfaces **206** of these interconnected dies **120**.

[0081] The first sequence **712** indicates an order or sequence in which consecutive chunks **704** of a burst of write data **702** are passed to the data buses **512** of the interconnected dies **120**. According to the first sequence **712**, the first chunk **704-1** is passed to the data bus **512** of the linked die **506**, and the second chunk **704-2** is passed to the data bus **512** of the interface die **504**. The first sequence **712** is maintained for subsequent bursts of write data **702**. For example, the third chunk **704-3** is passed to the data bus **512** of the linked die **506**, and the fourth burst of write data **702-4** is passed to the data bus **512** of the interface die **504**. In this manner, the linked die **506** writes odd-numbered chunks **704** to its memory array **204** (when starting to count from one), and the interface die **504** writes even-numbered chunks **704** to its memory array **204** (when starting to count from one).

[0082] There is a timing delay **714** associated with passing a chunk **704** from the interface die **504** to the linked die **506**. This timing delay **714** corresponds with the time it takes for the interface die **504** to transfer a chunk **704** to the linked die **506** through the interconnect **508**. In relative contrast, there is not a substantial time delay associated with passing a chunk **704** from the deserializer **710** to the data bus **512** of the interface die **504** because these components are each within, or part of, the interface die **504**.

[0083] Due to the first sequence **712**, a chunk **704** can be transferred to the linked die **506** as a following chunk **704** is received. For example, the interface die **504** transfers at least a portion of the first chunk **704-1** through the interconnect **508** to the linked die **506** while at least a portion of the second chunk **704-2** is received. In this way, the first chunk **704-1** can be present at the data bus **512** of the linked die **506** at approximately the same time that (or at least closer to the time that) the second chunk **704-2** is present at the data bus **512** of the interface die **504** (relative to an opposite

order). This enables the first chunk **704-1** and the second chunk **704-2** to be written to the respective memory arrays **204** of the linked die **506** and the interface die **504** at approximately the same time, or at least with some overlap to reduce the total write latency. By transferring the first chunk **704-1** to the linked die **506** instead of the second chunk **704-2** to the linked die **506**, the presence of the timing delay **714** can be masked such that an overall timing of the write operation can be impacted less, if at all, by the timing delay **714**.

[0084] FIG. **8** illustrates an example timing diagram **800** of a read operation in accordance with an asymmetric read-write sequence. In FIG. **8**, time progresses from left to right. During a read operation, the interface die **504** transmits a burst of read data **802** to the memory controller **114** or **418**. The burst of read data **802** includes a first chunk **804-1** and a second chunk **804-2**. The burst of read data **802** can include, for instance, 32 bytes in accordance with a mode of the memory device **108**. In example implementations, the first chunk **804-1** can correspond to an upper 16 bytes, and the second chunk **704-2** can correspond to a lower 16 bytes. In other words, the first chunk **804-1** can include a most-significant byte **708**, and the second chunk **804-2** can include the least-significant byte **706**. In total, the first chunk **704-1** and the second chunk **704-2** represent 32 bytes. Bursts of read data **802** can, however, be of different lengths, such as 16 bytes. In this case, each chunk **804** can represent 8 bytes of the burst of read data **802**.

[0085] To transmit the burst of read data **802** to the memory controller **114** or **418**, the interface die **504** reads the first chunk **804-1** from its memory array **204** and passes the first chunk **804-1** to a first-in first-out (FIFO) circuit **806** of the interface die **504** using the data bus **512** thereof. The first-in first-out circuit **806** can be implemented as part of the control circuitry **208** and/or the interface **206** of the interface die **504**. In general, the first-in first-out circuit **806** operates in a pipelined fashion.

[0086] During this time, the linked die **506** reads the second chunk **804-2** from its memory array **204** and transfers the second chunk **804-2** to the interface die **504** using the data bus **512** thereof and the interconnect **508**. A timing delay **808** is associated with transferring the second chunk **804-2** from the data bus **512** of the linked die **506** to the data bus **512** of the interface die **504**. The timing delay **808** corresponds with the time it takes for the linked die **506** to transfer the second chunk **804-2** to the interface die **504** through the interconnect **508**.

[0087] Meanwhile, the interface die **504** transmits the first chunk **804-1** to the memory controller **114** or **418** via the data pin **604**. In some cases, as the first chunk **804-1** is transmitted, the interface die **504** receives the second chunk **804** from the linked die **506** and passes the second chunk **804-2** to the first-in first-out circuit **806** using the data bus **512** thereof. The interface die **504** transmits the second chunk **804-2** to the memory controller **114** or **418** via the data pin **604**. By transmitting the first chunk **804-1**, as read from the interface die **504**, before transmitting the second chunk **804-2**, as read from the linked die **506**, the timing delay **808** can occur with at least some overlap as the interface die **504** transmits the first burst of read data **802-1**. As such, the presence of the timing delay **808** can be masked such that an overall timing of the read operation can be impacted less, if at all, by the timing delay **808**.

[0088] A second sequence **810** indicates an order or sequence in which consecutive chunks **804** of a burst of read data **802** are read from the interconnected dies **120**. According to the second sequence **810**, the first chunk **804-1** is read from the memory array **204** of the interface die **504**, and the second chunk **804-2** is read from the memory array **204** of the linked die **506**. Although not explicitly shown, the second sequence **810** can be maintained for subsequent bursts of read data **802**. In this manner, the interface die **504** reads and provides odd-numbered chunks **804** (when starting to count from one) chunks **804**, and the linked die **506** reads and provides even-numbered chunks **804** (when starting to count from one) of read data **802**.

[0089] The second sequence **810** represents an opposite or reverse sequence of the first sequence **712**. For example, the odd-numbered chunks **704** (when starting to count from one) are written to the linked die **506**, and the even-numbered chunks **704** (when starting to count from one) are

written to the interface die **504**. In contrast, odd-numbered chunks **804** (when starting to count from one) are read from the interface die **504**, and even-numbered chunks **804** (when starting to count from one) are read from the linked die **506**. Consider a situation in which a 32-byte burst of data is written to and read from the interconnected dies **120**. The 32 bytes of data include a lower 16 bytes as a first chunk of data and an upper 16 bytes as a second chunk of data. In this case, the upper 16 bytes is provided by the memory controller **114** or **418** to the interface die **504** as the second chunk **704-2** after providing the lower 16 bytes as the first chunk **704-1**. According to the asymmetric read-write sequence, the lower 16 bytes of data are written to the linked die **506** as the first chunk **704-1**, and the upper 16 bytes are written to the interface die **504** as the second chunk **704-2**. During the read operation, the interface die **504** reads the upper 16 bytes of data as the first chunk **804-1**, and the linked die **506** reads the lower 16 bytes of data as the second chunk **804-2**. In particular, interface die **504** transmits the lower 16 bytes of the burst of read data **802** to the memory controller **114** or **418** after transmitting the upper 16 bytes of the burst of read data **802**. In summation, the burst of read data **802** transmitted to the memory controller **114** or **418** is in an opposite order compared to the burst of write data **702** received from the memory controller **114** or **418**. More specifically, although the lower 16 bytes of the burst of write data **702** is received first during a write operation, the asymmetric read-write sequence causes the upper 16 bytes of the burst of read data **802** to be transmitted first during a read operation.

[0090] In this sense, the first sequence **712** and the second sequence **810** can also represent different chunk sequences, or byte orders, of data that passes through the interconnect **106** or **602**. For example, the first sequence **712** indicates that a lower set of bytes is transferred across the interconnect **106** or **602** prior to an upper set of bytes for write operations. In contrast, the second sequence **810** indicates that the upper set of bytes is transferred across the interconnect **106** or **602** prior to the lower set of bytes for read operations. These example chunk or byte orders may, however, be swapped between read and write operations.

Example Methods

[0091] This section describes example methods for implementing an asymmetric read-write sequence for interconnected dies with reference to the flow charts and flow diagrams of FIGS. **9** and **10**. These descriptions may also refer to components, entities, and other aspects depicted in FIGS. **1-6** by way of example only. The described methods are not necessarily limited to performance by one entity or multiple entities operating on one device.

[0092] FIG. **9** illustrates a flow diagram **900**, which includes operations **902** through **908**. These operations can be performed by a memory device **108** to implement aspects of an asymmetric read-write sequence for interconnected dies. At **902**, multiple dies that are interconnected within a memory device **108** receive a write request from a memory controller **114** or **418**. For example, the interconnected dies **120** receive the write request from the memory controller **114** or **418**. The write request can represent a memory command **424** shown in FIG. **4**. The write request is associated with a burst of write data **702**.

[0093] At **904**, the memory device **108** writes chunks **704** of the burst of write data **702** to the memory arrays **204** of the multiple dies **120** in accordance with a first sequence **712** responsive to receiving the write request. For example, the linked die **506** writes a first chunk **704-1** of the burst of write data **702**, and the interface die **504** writes a second chunk **704-2** of the burst of write data **702**, as shown in FIG. **7**. The first chunk **704-1** can correspond to a lower set of bytes, and the second chunk **704-2** can correspond to an upper set of bytes.

[0094] At **906**, the multiple dies **120** of the memory device **108** receive a read request from the memory controller **114** or **418**. The read request can represent a memory command **424** shown in FIG. **4**. The request is associated with a burst of read data **802**.

[0095] At **908**, the memory device **108** reads chunks **804** of the burst of read data **802** from the memory arrays **204** of the multiple dies **120** in accordance with a second sequence **810** responsive to receiving the read request. For example, the interface die **504** reads the first chunk **804-1** from

the memory array **204** thereof, and the linked die **506** reads the second chunk **804-2** from the memory array **204** thereof. The second sequence **810** is different than the first sequence **712**. In some aspects, the second sequence **810** can be considered a reverse order or an opposite order relative to the first sequence **712**.

[0096] FIG. **10** illustrates a flow diagram **1000**, which includes operations **1002** through **1004**. These operations can be performed by a memory controller **114** or **418** to implement aspects of an asymmetric read-write sequence for interconnected dies. At **1002**, the memory controller **114** or **418** transmits a burst of write data **702** to a data pin **604** of a die of multiple dies that are interconnected (e.g., from the interface die **504** of the set of interconnected dies **510**). The burst of write data **702** includes a first chunk **704-1** and a second chunk **704-2**, which have a first chunk order. The first chunk order can indicate, for example, that the first chunk **704-1** is associated with a lower set of bytes, and that the second chunk **704-2** is associated with an upper set of bytes. The memory controller **114** or **418** transmits the first chunk **704-1** prior to transmitting the second chunk **704-2**.

[0097] At **1004**, the memory controller **114** or **418** receives a burst of read data **802** from the data pin **604** of the die of the multiple dies that are interconnected (e.g., from the interface die **504** of the set of interconnected dies **510**). The burst of read data **802** includes a first chunk **804-1** and a second chunk **804-2**, which have a second chunk order that is opposite the first chunk order. The second chunk order can indicate, for example, that the first chunk **804-1** is associated with an upper set of bytes, and the second chunk **704-2** is associated with a lower set of bytes. The memory controller **114** or **418** receives the first chunk **804-1** prior to receiving the second chunk **804-2**.

[0098] In another example, the first chunk order can indicate that the first chunk **704-1** is associated with an upper set of bytes, and that the second chunk **704-2** is associated with a lower set of bytes. In this case, the second chunk order can indicate that the first chunk **804-1** is associated with a lower set of bytes, and that the second chunk **804-2** is associated with an upper set of bytes.

[0099] In general, the asymmetric read-write sequence causes the second chunk order to be opposite the first chunk. As such, the memory controller **114** or **418** can perform an additional operation to cause data associated with the write and read operations to have a same order when communicated with another entity, such as the processor **110**. For example, the memory controller **114** or **418** can transmit, to the processor **110**, the second chunk **804-2** of the burst of read data **802** prior to transmitting the first chunk **804-1** of the burst of read data **802**.

[0100] For the flow charts and flow diagrams described above, the orders in which operations are shown and/or described are not intended to be construed as a limitation. Any number or combination of the described process operations can be combined or rearranged in any order to implement a given method or an alternative method. Operations may also be omitted from or added to the described methods. Further, described operations can be implemented in fully or partially overlapping manners.

[0101] Aspects of these methods or operations may be implemented in, for example, hardware (e.g., fixed-logic circuitry or a processor in conjunction with a memory), firmware, or some combination thereof. The methods may be realized using one or more of the apparatuses, systems, or components shown in FIGS. **1**-**6**, the components of which may be further divided, combined, rearranged, and so on. The devices, systems, and components of these figures generally represent firmware, such as executable-code or the actions thereof; hardware, such as electronic devices, packaged modules, IC chips, or circuits; software, such as processor-executable instructions; or a combination thereof. The illustrated apparatuses **102** and components of **200**, include, for instance, a memory controller **114**, an interconnect **106**, and a memory device **108**. FIGS. **1**-**6** illustrate some of the many possible systems or apparatuses capable of implementing the described methods.

[0102] Computer-readable media includes both non-transitory computer storage media and communication media including any medium that facilitates transfer of a computer program (e.g.,

an application) or data from one entity to another. Non-transitory computer storage media can be any available medium accessible by a computer, such as RAM, ROM, Flash, EEPROM, optical media, and magnetic media.

[0103] Unless context dictates otherwise, use herein of the word "or" may be considered use of an "inclusive or," or a term that permits inclusion or application of one or more items that are linked by the word "or" (e.g., a phrase "A or B" may be interpreted as permitting just "A," as permitting just "B," or as permitting both "A" and "B"). Also, as used herein, a phrase referring to "at least one of" a list of items refers to any combination of those items, including single members. For instance, "at least one of a, b, or c" can cover a, b, c, a-b, a-c, b-c, and a-b-c, as well as any combination with multiples of the same element (e.g., a-a, a-a-a, a-a-b, a-a-c, a-b-b, a-c-c, b-b, b-b-b, b-b-c, c-c, and c-c-c, or any other ordering of a, b, and c). Further, items represented in the accompanying figures and terms discussed herein may be indicative of one or more items or terms, and thus reference may be made interchangeably to single or plural forms of the items and terms in this written description.

CONCLUSION

[0104] Although aspects of implementing an asymmetric read-write sequence for interconnected dies have been described in language specific to certain features and/or methods, the subject of the appended claims is not necessarily limited to the specific features or methods described. Rather, the specific features and methods are disclosed as a variety of example implementations of implementing an asymmetric read-write sequence for interconnected dies.

Claims

1. A method comprising: receiving, by multiple dies that are interconnected, a write request from a memory controller, the write request associated with a burst of write data; writing chunks of the burst of write data to memory arrays of the multiple dies in accordance with a first sequence responsive to receiving the write request; receiving, by the multiple dies, a read request from the memory controller, the read request associated with a burst of read data; and reading chunks of the burst of read data from the memory arrays of the multiple dies in accordance with a second sequence responsive to receiving the read request, the second sequence being different than the first sequence.

2. The method of claim 1, wherein the second sequence is a reverse order of the first sequence.

3. The method of claim 1, further comprising: receiving, via a first data pin of a first die of the multiple dies, the chunks of the burst of write data, the chunks of the burst of write data comprising a first chunk and a second chunk; transferring, via a second data pin of the first die, the first chunk to a second die of the multiple dies; writing the second chunk to a memory array of the first die in accordance with the first sequence; receiving, via a third data pin of the second die, the first chunk; and writing the first chunk to a memory array of the second die in accordance with the first sequence.

4. The method of claim 3, further comprising: causing a timing delay associated with the transfer of the first chunk from the first die to the second die to occur during at least a portion of time that the receiving of the second chunk occurs.

5. The method of claim 3, further comprising: writing at least a portion of the second chunk to the memory array of the first die while the writing of at least a portion of the first chunk to the memory array of the second die occurs.

6. The method of claim 3, wherein: the first chunk comprises a least-significant byte of the burst of write data; and the second chunk comprises a most-significant byte of the burst of write data.

7. The method of claim 1, wherein: the chunks of the burst of read data comprise a first chunk and a second chunk; and the method further comprises: reading the first chunk from a memory array of a first die of the multiple dies in accordance with the second sequence; transmitting, via a data pin

of the first die, the first chunk to the memory controller; reading the second chunk from a memory array a second die of the multiple dies in accordance with the second sequence; transferring, via a connected data pin of the second die, the second chunk to the first die; receiving, via a connected data pin of the first die, the second chunk from the second die; and transmitting, via the data pin of the first die, the second chunk to the memory controller.

8. The method of claim 7, further comprising: causing a timing delay associated with the transfer of the second chunk from the second die to the first die to occur during at least a portion of time that the transmitting of the first chunk occurs.

9. The method of claim 7, further comprising: transferring the second chunk to the first die while the transmitting of at least a portion of the first chunk to the memory controller occurs.

10. An apparatus comprising: multiple dies that are interconnected, the multiple dies comprising: a first die configured to communicate data with a memory controller without the data propagating through another die of the multiple dies that are interconnected; a second die configured to communicate data with the memory controller via the first die; and an interconnect coupled between the first die and the second die, the multiple dies jointly configured to: write chunks of a burst of write data to the first die and the second die in accordance with a first sequence; and read chunks of a burst of read data from the first die and the second die in accordance with a second sequence that is different than the first sequence.

11. The apparatus of claim 10, wherein the second sequence is a reverse order of the first sequence.

12. The apparatus of claim 10, wherein: the first die comprises: a first data pin configured to be coupled to the memory controller; a second data pin; and a first memory array; and the second die comprises: a third data pin coupled to the second data pin of the first die via the interconnect; and a second memory array.

13. The apparatus of claim 12, wherein the second die comprises a fourth data pin, the fourth data pin configured to be inactive.

14. The apparatus of claim 13, wherein the fourth data pin is configured to be operably decoupled from the memory controller during the writing of the chunks of the burst of write data and during the reading of the chunks of the burst of read data.

15. The apparatus of claim 12, further comprising: a third die comprising: a fourth data pin configured to be coupled to the memory controller; a fifth data pin; and a third memory array; and a fourth die comprising: a sixth data pin coupled to the fifth data pin of the third die; and a fourth memory array, the third die and the fourth die jointly configured to perform an asymmetric read-write sequence.

16. The apparatus of claim 10, wherein: the chunks of the burst of write data comprise: a first chunk associated with a lower set of bytes; and a second chunk associated with an upper set of bytes; the chunks of the burst of read data comprise: a first chunk associated with another upper set of bytes; and a second chunk associated with another lower set of bytes.

17. The apparatus of claim 16, wherein the first die is configured to: receive the first chunk of the burst of write data prior to receiving the second chunk of the write data from the memory controller; and transmit the first chunk of the burst of read data prior to transmitting the second chunk of the read data to the memory controller.

18. The apparatus of claim 16, wherein: the first die is configured to: write the second chunk of the burst of write data to a memory array of the first die in accordance with the first sequence; and read the first chunk of the burst of read data from the memory array of the first die in accordance with the second sequence; and the second die is configured to: write the first chunk of the burst of write data to a memory array of the second die in accordance with the first sequence; and read the second chunk of the burst of read data from the memory array of the second die in accordance with the second sequence.

19. The apparatus of claim 10, wherein: the apparatus comprises a Compute Express Link® (CXL®) device; and the memory controller is coupled to the first die and the second die via an

interconnect that is internal to the CXL device.

20. The apparatus of claim 10, further comprising: a substrate, wherein the first die and the second die are disposed on the substrate.