exFAT IP Core for NVMe

Design Gateway Co.,Ltd

E-mail: ip-sales@design-gateway.com
URL: www.design-gateway.com

Core Facts

Provided with Core	
Documentation	Reference Design Manual Demo Instruction Manual
Design File Formats	Encrypted netlist file
Instantiation Templates	VHDL
Reference Designs & Application Notes	Vivado Project, See Reference Design Manual
Additional Items	Demo on KCU105/ZCU106 ZCU102/VCU118/
Support	

Features

- Access NVMe device as exFAT system without using CPU and external memory
- Simple user interface and operating with DG NVMe IP, NVMeG3 IP
- Achieve the best write/read speed, similar to raw data format by using DG NVMe IP, NVMeG3 IP
- Support device capacity: 8 Gigabyte* – 64 Petabyte*
  *Gigabyte means 1024x1024x1024 byte while Petabyte means 1024x1024x1024x1024x1024 byte
- Support only 512-byte LBA unit
- Four user commands - Format, Write file, Read file and Shutdown
- Support eight file sizes* - 32MB, 128MB, 512MB, 2GB, 8GB, 32GB, 128GB and 512GB
  *Some file sizes are not available for some device capacities, as shown in Table 2
- Reference design available on KCU105, ZCU102, ZCU106 and VCU118 board with AB18-PCIeX16, AB17-M2FMC and AB16-PCIeXOVR adapter board

Table 1: Example Implementation Statistics for Ultrascale device

Family	Example Device	Fmax (MHz)	CLB Regs	CLB LUTs	CLB	IOB	BRAMTile[1]	PLL	GTX	Design Tools
Kintex-Ultrascale	XCKU040FFVA1156-2E	300	2661	2772	566	-	4	-	-	Vivado2017.4
Zynq-Ultrascale+	XCZU7EV-FFVC1156-2E	300	2663	2763	587	-	4	-	-	Vivado2017.4
Virtex-Ultrascale+	XCVU9P-FLGA2104-2L	300	2661	2764	576	-	4	-	-	Vivado2017.4

Applications

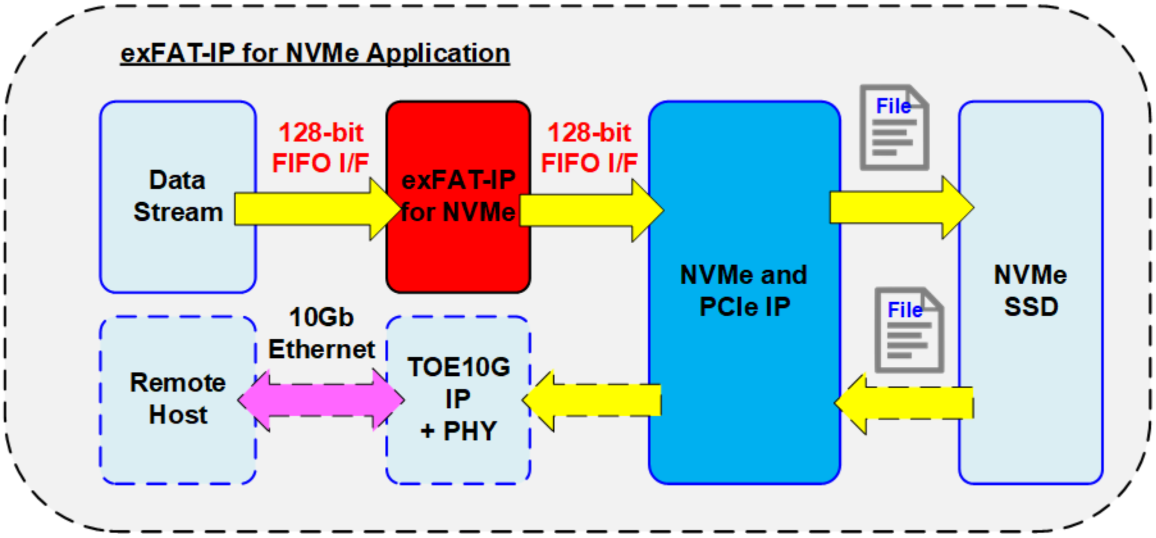

Figure 1: exFAT IP for NVMe Application

exFAT IP for NVMe must integrated with DG NVMe IP and low layer hardware for PCIe interface. The IP core is an ideal to access NVMe device as exFAT file system with ultra speed performance, similar to raw data access. This solution fits the application which needs to record data to NVMe device by FPGA, but the data file is read by other hosts such as PC based on file system format. As shown in Figure 1, data stream is recorded to NVMe SSD via exFAT IP system. While read data interface is connected to TOE10G IP to allow the remote host reading recorded file via 10Gb Ethernet. The full system is implemented without using external memory such as DDR.

General Description

Typically, file system is implemented by using the software run on CPU for writing or reading data as a file. So, the system must include CPU and memory for storing CPU firmware. Write performance and Read performance when accesssing the device as file system by using CPU firmware are not good. There is much overhead time for CPU managing file system which is effect to reduce the performance. Finally, when high performance under file system is necessary, the customized file system is applied, not standard file system.

To achieve the above streategy, exFAT IP for NVMe is implemented as CPUless system for writing or reading data in exFAT file system format at very high speed, like raw data access. exFAT IP for NVMe is top-up module of NVMe(G3) IP for accessing as file system instead of raw data which is default mode of NVMe(G3) IP. The user interface of exFAT IP for NVMe is mostly similar to NVMe(G3) IP for easy usage. It consists of control interface and data interface.

While NVMe(G3) IP uses physical parameters, exFAT IP uses file parameters instead. The index of start point to write/read data is File name instead of physical address. The transfer size to write/read data is the amount of written/read files, instead of transfer size in 512-byte unit. Four commands are designed in exFAT IP to access NVMe device - Format, Write file, Read file and Shutdown.

Similar to NVMe(G3) IP, data interface of exFAT IP is designed by using general FIFO interface. Also, exFAT IP must use the same clock as user clock of NVMe(G3) IP because there is no asynchronous circuit inside exFAT IP to interface with user logic and NVMe(G3) IP.

The additional parameters of exFAT IP are created date, created time, and file size. Created date and created time are applied when running Format and Write File command to be created date and time of empty directory and file respectively. Also, file size must be set when running Format operation which can support up to eight size depending on device capacity - 32 MB, 128 MB, 512 MB, 2 GB, 8 GB, 32 GB, 128 GB and 512 GB. More details of supported file size are shown in Table 2.

Table 2: Supported file size following device capacity

Device capacity	32MB(2)	128MB(2)	512MB(2)	2GB(2)	8GB(2)	32GB(2)	128GB(2)	512GB(2)
8 GB - 16 GB(1)	Yes	Yes	Yes	Yes	No	No	No	No
16 GB – 64 GB(1)	Yes	Yes	Yes	Yes	Yes	No	No	No
64 GB – 256 GB(1)	Yes	Yes	Yes	Yes	Yes	Yes	No	No
256 GB – 1 TB(1)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
1 TB – 512 TB(1)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
512 TB – 8 PB(1)	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
8 PB – 64 PB(1)	No	No	Yes	Yes	Yes	Yes	Yes	Yes

Note

(1) The upper limit of device capacity must be less than this value. For example, when device capacity is 512 TB, user checks supported file size from row 512 TB – 8 PB, not 1TB – 512 TB.

(2) MB means 1024x1024 byte. GB means 1024x1024x1024 byte.
TB means 1024x1024x1024x1024 byte. PB means 1024x1024x1024x1024x1024 byte.

After finishing Format command, file size cannot be changed. It needs to rerun Format command when the user wants to set the new file size. After running Format command, 512 empty directories are created in the device, i.e, DIR000, DIR001, …, DIR0FF, DIR100, … , DIR1FE, and DIR1FF. Directory name uses three hexadecimal digits to refer directory number. For example, DIR0FF is Directory number 255.

Though 512 directories are created by Format command, some directories are always empty. All directories are used in some cases, as shown in Table 3.

When running Write file command, the new file is created in the directory. Filename is fixed to seven hexadecimal digits, beginning from 0000000.BIN which is stored in DIR000. The next files (0000001.BIN, 0000002.BIN, …) are stored to the same directory (DIR000) until total amount of files stored in current directory is equal to maximum amount of files per directory (DirCap signal). After that, the next file is stored to the next directory number (DIR001). Maximum amount of files per directory depends on device capacity, as shown in Table 3.

Table 3: Maximum amount of files per directory (DirCap)

Device capacity	Minimum file size	DirCap[19:0]	Used directory
8 GB - 32 GB(1)	32MB	0x00100 (256)	DIR000 - DID003
32 GB – 128 GB(1)	32MB	0x00200 (512)	DIR000 - DIR007
128 GB – 512 GB(1)	32MB	0x00400 (1024)	DIR000 – DIR00F
512 GB – 2 TB(1)	32MB	0x00800 (2048)	DIR000 – DIR01F
2 TB – 8 TB(1)	32MB	0x01000 (4096)	DIR000 – DIR03F
8 TB – 32 TB(1)	32MB	0x02000 (8192)	DIR000 – DIR07F
32 TB – 128 TB(1)	32MB	0x04000 (16384)	DIR000 – DIR0FF
128 TB – 512 TB(1)	32MB	0x08000 (32768)	DIR000 – DIR1FF
512 TB – 2 PB(1)	128MB	0x10000 (65536)	DIR000 – DIR0FF
2 PB – 8 PB(1)	128MB	0x20000 (131072)	DIR000 – DIR1FF
8 PB – 32 PB(1)	512MB	0x40000 (262144)	DIR000 – DIR0FF
32 PB – 64 PB(1)	512MB	0x80000 (524288)	DIR000 – DIR0FF

Note (1) The upper limit of device capacity must be less than this value. For example, when device capacity is 32 GB, user checks DirCap from row 32 GB – 128 GB, not 8 GB – 32 GB.

Functional Description

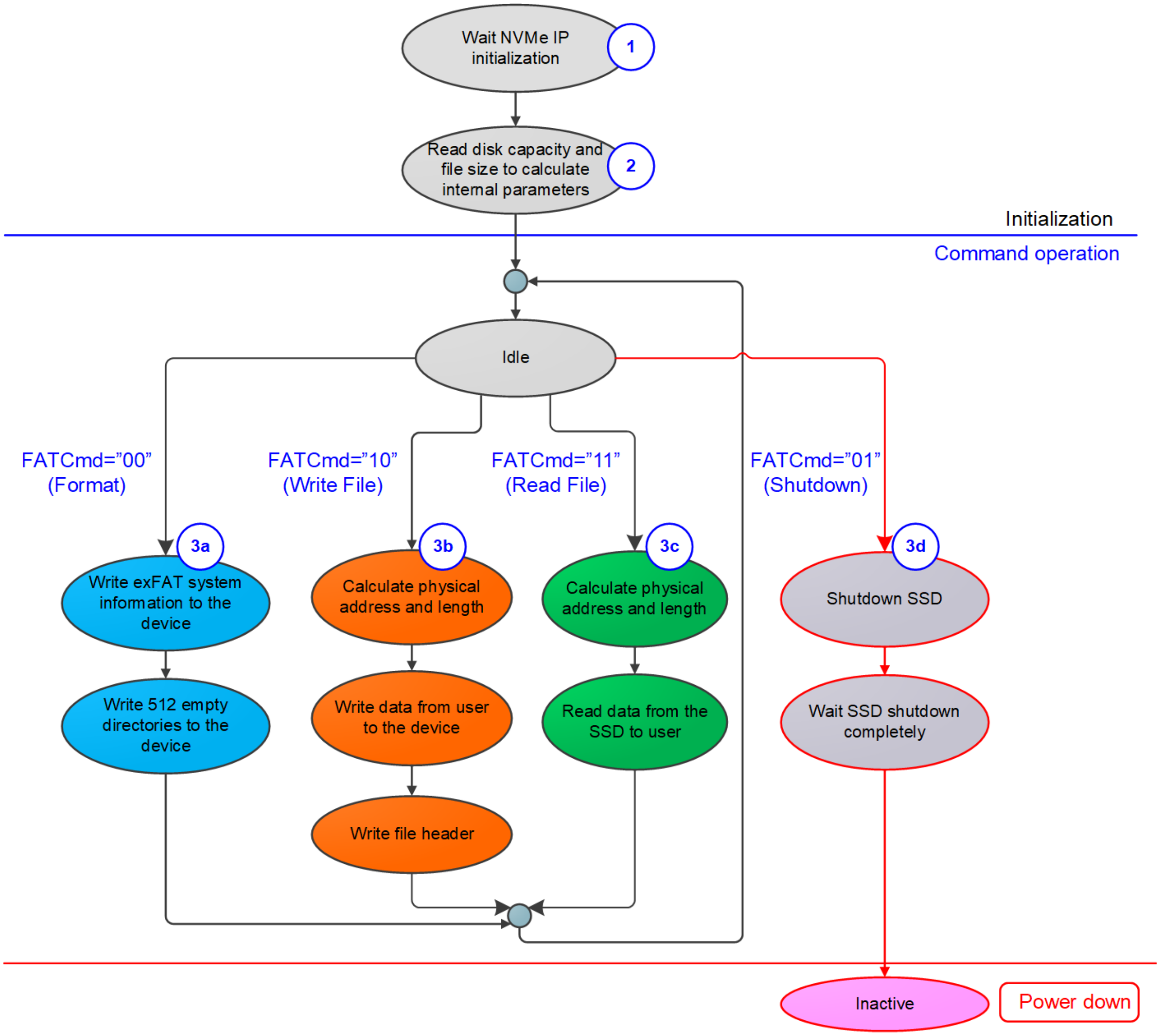
Wait NVMe IP initialization
1
Read disk capacity and file size to calculate internal parameters
2
Initialization
Command operation
Idle
FATCmd="00" (Format)
FATCmd="10" (Write File)
FATCmd="11" (Read File)
FATCmd="01" (Shutdown)
3a
Write exFAT system information to the device
Write 512 empty directories to the device
3b
Calculate physical address and length
Write data from user to the device
Write file header
3c
Calculate physical address and length
Read data from the SSD to user
3d
Shutdown SSD
Wait SSD shutdown completely
Inactive
Power down

Figure 2: exFAT IP for NVMe Operation

The sequence of exFAT IP Core for NVMe operation is as follows:

1) exFAT IP waits until NVMe(G3) IP completes NVMe device initialization.

2) exFAT IP sends Identify command to NVMe(G3) IP to get device information such as device capacity. After that, file information for this device are updated such as current file size (DiskFSize) and the amount of files (DiskFnum). After finishing Identify command, exFAT IP is ready to receive new command from user, i.e., Format, Write file, Read file, and Shutdown.

   Note: File information of the device may be incorrect if the device is not formatted by exFAT IP.

3) The details for each command are described as follows.

   a) For the new device which is not formatted by exFAT IP, Format command must be run firstly to clean up the device, set up file system, and create 512 empty directories. Besides, Format command is necessary to change file size in the device. After finishing Format command, the amount of files which are output from exFAT IP is reset to 0 (the device is empty).

   b) When user selects Write file command, the first file name (UserFName) and the amount of written files (UserFLen) are received from user. File name and the amount of written files are converted to be physical address and total transfer size in 512-byte unit for setting to NVMe(G3) IP. After that, the Write command request is asserted to NVMe(G3) IP. Next, data from user is forwarded to NVMe(G3) IP until total data are completely transferred. Finally, exFAT IP writes file header to link the user data to each file name.

   Note:

   - *File header is filled to the device as the final step. If system is powered down during writing file command, the file will be lost or corrupt.*
   - *exFAT IP does not validate the input value, so User logic must not send out-of-range input to exFAT IP.*

   c) Similar to Write file command, the first process of Read file command is to calculate start physical address and total transfer size from user inputs (the first file name and the amount of read files) for setting to NVMe(G3) IP. After that, exFAT IP asserts the Read command request to NVMe(G3) IP. Finally, data is returned from NVMe(G3) IP to user until total data are completely transferred.

   d) The last command which user must be sent before shutdown system is Shutdown command. This command is used to shutdown device in a good sequence. Without Shutdown command, Write data in device cannot be guaranteed. Some data may be remained in the cache within the device and do not flush to flash memory. As a result, the write data may be lost if the system is power down without Shutdown command. After running Shutdown command, NVMe(G3) IP and device change to the Inactive state.

exFAT IP for NVMe

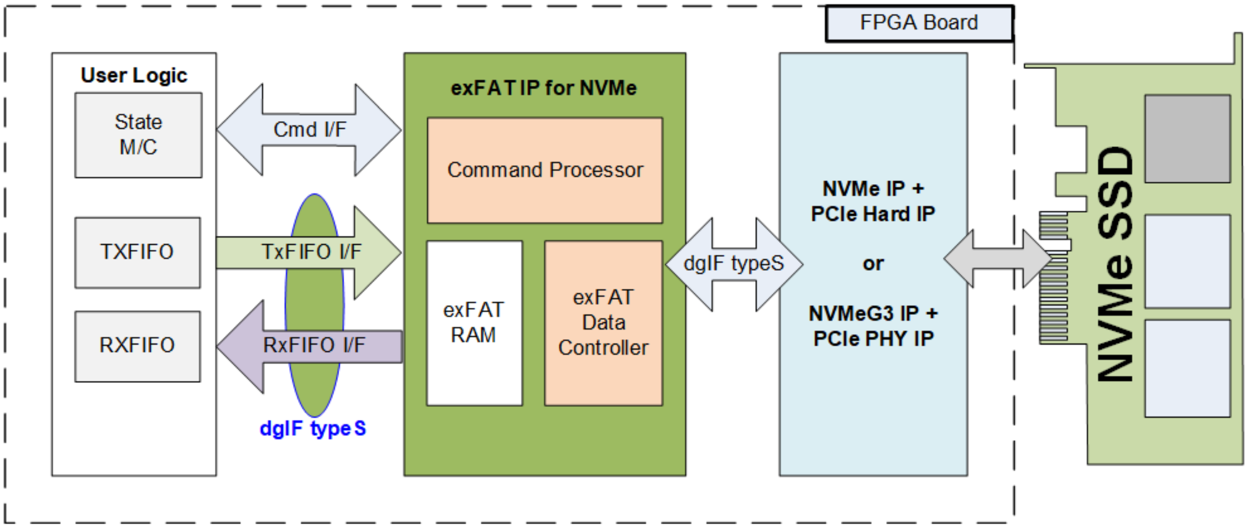

Figure 3: exFAT IP for NVMe Block Diagram

As shown in Figure 3, there are three submodules inside the IP, i.e., Command processor, Data Controller, and exFAT RAM. Command processor handles the user control interface while Data controller handles the user data interface and NVMe(G3) IP. exFAT RAM stores the internal file parameters transferring between Command processor and Data controller. More details of each submodule are described as follows.

- **Command processor**

  This module controls the order to transfer the command, the data, and the status in each transfer direction with NVMe(G3) IP for operating each command, as shown in Figure 2. The signals of other modules are always controlled and monitored by Command processor. Besides, it consists of many calculation units for converting file parameters from user to be physical parameters for NVMe(G3) IP. Most file parameters depend on file size and device capacity.

- **exFAT RAM**

  This RAM is implemented by BlockRAM to store file system data. RAM size is 1024x128-bit.

- **Data controller**

  exFAT IP stores three data types in NVMe SSD, i.e., raw data, file system data, and file parameters. Raw data is the data in the file which is transferred through FIFO interface of user logic. File system data is constant value which is stored in exFAT RAM. File parameters are the internal parameters which must be calculated from the user inputs and some internal parameters.

DG NVMe IP or NVMeG3 IP

exFAT IP for NVMe is the top-up module of NVMe IP or NVMeG3 IP. Both NVMe IP and NVMeG3 IP implement as host controller to access NVMe SSD via PCIe interface with the same NVMe features. The difference bewteen NVMe IP and NVMeG3 IP is in low layer boundary of PCIe.

When exFAT IP is integrated with NVMe IP, the low layer hardware is implemented by using Integrated Block for PCI Express (PCIe hard IP) from Xilinx. The details of NVMe IP are described in the datasheet which can be downloaded from following link.

https://dgway.com/products/IP/NVMe-IP/dg_nvme_ip_data_sheet_en.pdf

When exFAT IP is integrated with NVMeG3 IP (NVMe IP with PCIe Soft IP) instead of NVMe IP, Data link layer and some parts of Physical layer of PCIe protocol are implemented in NVMeG3 IP. Thus, NVMeG3 IP connects with Xilinx PCIe PHY to completely implement PCIe Physical layer. More details of NVMeG3 IP are described in the datasheet which can be downloaded from following link.

https://dgway.com/products/IP/NVMe-IP/dg_nvmeg3_ip_data_sheet_xilinx_en.pdf

User Logic

This module could be designed by using small state machine to send command with other parameters for exFAT IP. Two FIFOs are used to be file data buffer when running Write file and Read file command. However, exFAT IP reference design includes CPU to use Serial console as user interface for setting the input parameters and displaying test result and status.

Core I/O Signals

Description of all I/O signals of exFAT IP is provided in Table 4.

Table 4 Core I/O Signals

Signal	Dir	Description
Clock and Reset		
RstB	In	Synchronous reset signal on Clk domain. Active low. De-assert to '1' after Clk signal is stable.
Clk	In	User clock which must be the same clock as Clk input of NVMe(G3) IP. The frequency must be more than or equal to PCIeClk which is output from PCIe hard IP (125 MHz for PCIe Gen2, 250 MHz for PCIe Gen3)
User Interface (Command)		
FSize[2:0]	In	File size: "000": 32MB, "001": 128MB, "010": 512MB, "011": 2GB, "100": 8GB, "101": 32GB, "110": 128GB, "111": 512GB This input is used in Fomat command only. **Note: 1 MB is 1024x1024 byte and 1 GB is 1024x1024x1024 byte**
FDateY[6:0]	In	Year in created date, count from 1980 (For example, FDateY=39 is year 2019). Please see note in FTimeS description.
FDateM[3:0]	In	Month in created date. Valid from 1-12 (1=Jan, 2= Feb, …). Please see note in FTimeS description.
FDateD[4:0]	In	Day in created date. Valid from 1-31. Please see note in FTimeS description.
FTimeH[4:0]	In	Hour in created time. Valid from 0-23. Please see note in FTimeS description.
FTimeM[5:0]	In	Minute in created time. Valid from 0-59. Please see note in FTimeS description.
FTimeS[4:0]	In	x2 sec in created time. Valid from 0-29 (1=2, 2=4, …). **Note: FDateY, FDateM, FDateD, FTimeH, FTimeM and FTimeS are applied to be created time of directory in Format command or created time of file in Write file command.**
UserCmd[1:0]	In	User Command. "00": Format command, "01": Shut down, "10": Write file, "11": Read file.
UserFName[26:0]	In	The first file name to write/read file (0="0000000.BIN", 1="0000001.BIN", …). Valid from 0 to TotalFCap - 1. This input is used in Write file and Read file command. When running Write file command, this value must be less than or equal to DiskFnum signal. It is recommended to set this value equal to DiskFnum in Write file command. Therefore, the first file name of the new write command is the next value from the last file in the device.
UserFLen[26:0]	In	Total files for transferring in the request. Valid from 1 to (TotalFCap – UserFName). This input is used in Write file and Read file command.
UserReq	In	Assert to '1' to send the new command request with the valid value on FSize, UserCmd, UserFName, UserFLen, FDateYMD, and FTimeHMS. Each command needs different input parameters. This signal is asserted to '1' when the IP is Idle only (UserBusy='0').
UserBusy	Out	Assert to '1' when IP is busy.
TotalFCap[26:0]	Out	Maximum amount of files to store in NVMe device. This value is valid after exFAT IP completes initialization process (UserBusy='0'). Please see note in DiskFnum description.
DirCap[19:0]	Out	Maximum amount of files to store in one directory. This value is valid after exFAT IP completes initialization process (UserBusy='0').
DiskFsize[2:0]	Out	Current file size used in NVMe device. This signal is valid after exFAT IP completes initialization process (UserBusy='0'). Please see note in DiskFnum description.

Signal	Dir	Description
User Interface (Command)		
DiskFnum[26:0]	Out	The amount of files stored in the device. This signal is valid after exFAT IP completes the initialization process or Write command process (UserBusy='0'). **Note: TotalFCap, DiskFsize and DiskFnum will be incorrect if NVMe device has never been formatted by exFAT IP.**.
UserError	Out	Error flag. Asserted to '1' when UserErrorType is not equal to 0. The flag is cleared to '0' by asserting RstB signal to NVMe(G3) IP and exFAT IP.
UserErrorType[31:0]	Out	[23:0] - Direct mapped to NVMeErrorType signal of NVMe(G3) IP. Please see more details in NVMe IP or NVMeG3 IP datasheet. [24] - Error when device capacity is out of range (more than or equal to 64 PetaByte or less than 8 GigaByte) [25] – Error when LBA unit of NVMe SSD is not equal to 512 byte.
IPVesion[31:0]	Out	IP version number
TestPin[63:0]	Out	Reserved to be IP test point.
User Interface (Data)		
UserFifoWrCnt[15:0]	In	Write data counter of Rx FIFO. Used to check full status. If FIFO data count is less than 16-bit, please fill '1' to upper bit. UserFifoWrEn can be asserted to '1' when UserFifoWrCnt[15:6] is not equal to all 1.
UserFifoWrEn	Out	Asserted to '1' to write data to Rx FIFO when receiving data from NVMe SSD through NVMe(G3) IP during running Read file command.
UserFifoWrData[127:0]	Out	Write data bus of Rx FIFO. Valid when UserFifoWrEn='1'.
UserFifoRdCnt[15:0]	In	Read data counter of Tx FIFO. Used to check total amount of data stored in FIFO. If FIFO data count is less than 16-bit, please fill '0' to upper bit.
UserFifoEmpty	In	This signal is unused for this IP.
UserFifoRdEn	Out	Asserted to '1' to read data from Tx FIFO and forward to NVMe SSD through NVMe(G3) IP during running Write file command.
UserFifoRdData[127:0]	In	Read data returned from Tx FIFO. Valid in the next clock after UserFifoRdEn is asserted to '1'.
NVMe(G3) IP User Interface (Connect to dgIF typeS of NVMe(G3) IP) (Please see more details from NVMe IP or NVMeG3 IP datasheet)		
NVMeCmd[2:0]	Out	Connect to UserCmd of NVMe(G3) IP
NVMeAddr[47:0]	Out	Connect to UserAddr of NVMe(G3) IP
NVMeLen[47:0]	Out	Connect to UserLen of NVMe(G3) IP
NVMeReq	Out	Connect to UserReq of NVMe(G3) IP
NVMeBusy	In	Connect to UserBusy of NVMe(G3) IP
NVMeLBASize[47:0]	In	Connect to LBASize of NVMe(G3) IP
NVMeLBAMode	In	Connect to LBAMode of NVMe(G3) IP
NVMeCtmSubmDW0[31:0] - NVMeCtmSubmDW15[31:0]	Out	Connect to CtmSubmDW0 – CtmSubmDW15 of NVMe(G3) IP
NVMeError	In	Connect to UserError of NVMe(G3) IP
NVMeErrorType[31:0]	In	Connect to UserErrorType of NVMe(G3) IP

Signal	Dir	Description
NVMe(G3) IP User Interface (Connect to dgIF typeS of NVMe(G3) IP) (Please see more details from NVMe IP or NVMeG3 IP datasheet)		
NVMeFifoWrCnt[15:0]	Out	Connect to UserFifoWrCnt of NVMe(G3) IP
NVMeFifoWrEn	In	Connect to UserFifoWrEn of NVMe(G3) IP
NVMeFifoWrData[127:0]	In	Connect to UserFifoWrData of NVMe(G3) IP
NVMeFifoRdCnt[15:0]	Out	Connect to UserFifoRdCnt of NVMe(G3) IP
NVMeFifoEmpty	Out	Connect to UserFifoEmpty of NVMe(G3) IP
NVMeFifoRdEn	In	Connect to UserFifoRdEn of NVMe(G3) IP
NVMeFifoRdData[127:0]	Out	Connect to UserFifoRdData of NVMe(G3) IP

Timing Diagram

Initialization

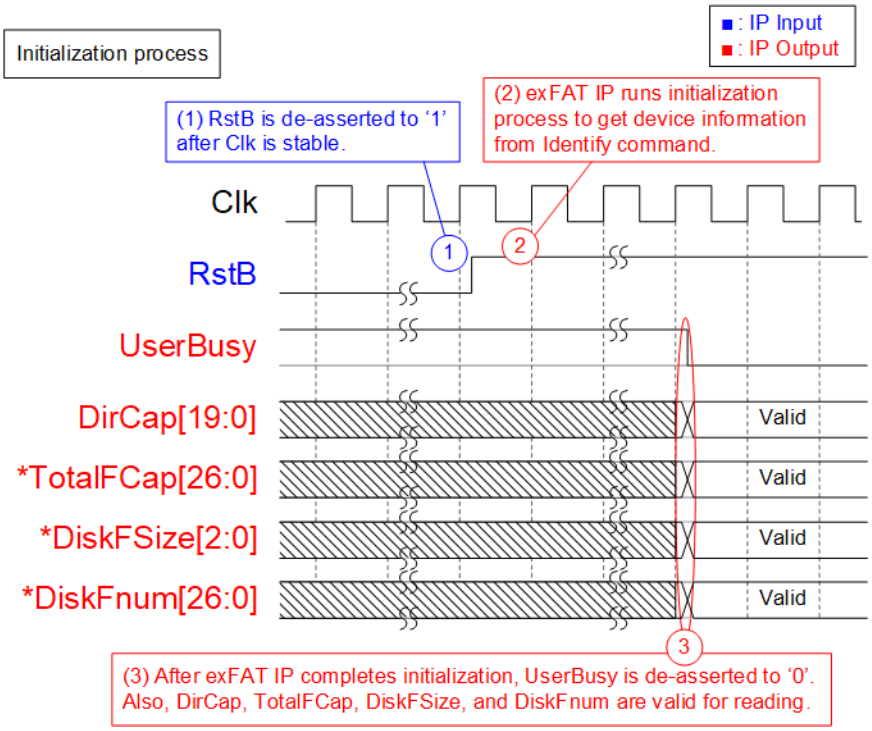
Initialization process
■ : IP Input
■ : IP Output
(1) RstB is de-asserted to '1' after Clk is stable.
(2) exFAT IP runs initialization process to get device information from Identify command.
Clk
RstB
UserBusy
DirCap[19:0]
*TotalFCap[26:0]
*DiskFSize[2:0]
*DiskFnum[26:0]
Valid
Valid
Valid
Valid
1
2
3
(3) After exFAT IP completes initialization, UserBusy is de-asserted to '0'. Also, DirCap, TotalFCap, DiskFSize, and DiskFnum are valid for reading.

Figure 4: exFAT IP for NVMe Intialization

The steps of the initialization process are as follows.

1) RstB is de-asserted to '1' by user after Clk is stable.
2) exFAT IP begins initialization process by sending Identify command to NVMe(G3) IP. After that, device information returned from Identify command is processed by exFAT IP to calculate file system information.
3) UserBusy is de-asserted to '0' after exFAT IP finishes processing Identify data from NVMe(G3) IP. Next, four output signals from exFAT IP to show device information are valid to read, i.e., DirCap (maximum amount of files per directory), TotalFCap (maximum amount of files stored in device), DiskFsize (file size in device) and DiskFnum (total amount of files stored in device).

After finishing the above sequence, exFAT IP is ready to receive the new command from user. Four commands can be selected for exFAT IP opreating with assigning the input signals. The inputs for each command are different. Please see more details in the next topic.

**Note: DirCap is always reliable after completing initialization sequenc. However, TotalFCap, DiskFsize and DiskFnum are valid only when the device has been formatted by exFAT IP. Otherwise, TotalFCap, DiskFsize and DiskFnum are incorrect.*

Format command

Format command is necessary if some of following conditions are met.

1) The device has never been formatted by exFAT IP.
2) User needs to delete all files in the device.
3) User needs to change file size in the device.

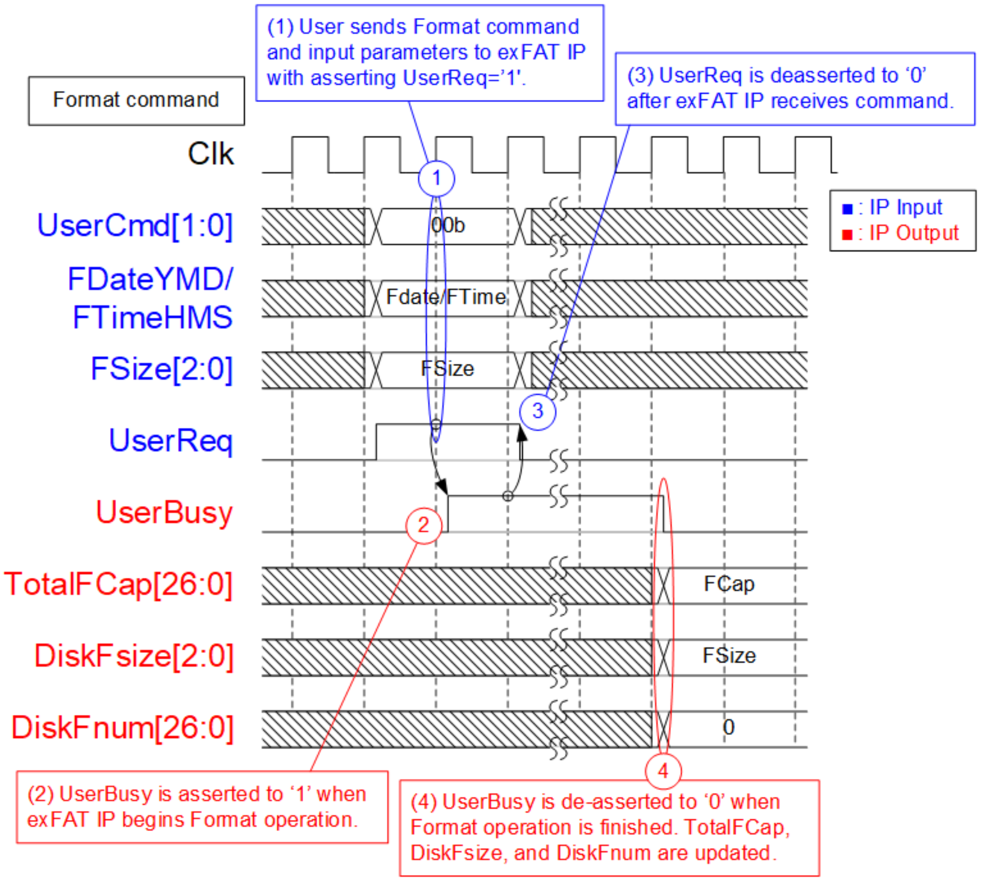
Format command
(1) User sends Format command and input parameters to exFAT IP with asserting UserReq='1'.
(3) UserReq is deasserted to '0' after exFAT IP receives command.
■ : IP Input
■ : IP Output
Clk
UserCmd[1:0]
00b
FDateYMD/
FTimeHMS
Fdate/FTime
FSize[2:0]
FSize
UserReq
UserBusy
TotalFCap[26:0]
FCap
DiskFsize[2:0]
FSize
DiskFnum[26:0]
0
1
2
3
4
(2) UserBusy is asserted to '1' when exFAT IP begins Format operation.
(4) UserBusy is de-asserted to '0' when Format operation is finished. TotalFCap, DiskFsize, and DiskFnum are updated.

Figure 5: Timing diagram of Format command

The example steps of control interface to run Format command are as follows.

1) User sets UserCmd = 00b (Format), FDate (created date), FTime (created time), and FSize (file size to write in Write file command) with asserting UserReq to '1'.
2) exFAT IP asserts UserBusy to '1' and starts Format command operation following the input parameters.
3) UserReq is de-asserted to '0' to complete the current request. Then, user logic waits until Format operation is finished by monitoring UserBusy.
4) UserBusy is de-asserted to '0' after finishing creating file system information. 512 empty directories (DIR000 – DIR1FF) is created in the device. TotalFCap (maximum amount of files in the device), DiskFsize (file size setting in the device), and DiskFnum (total amount of files in the device) are updated. DiskFsize is equal to Fsize input during Format command request while DiskFnum is reset to 0 (device is empty). Created date and created time of empty directory are equal to FDataYMD and FTimeHMS input.

Shutdown command

Shutdown command is recommended to send as the last command before power down the system. When Shutdown command is issued, SSD flushes the data from the internal cache to flash memory. After finishing this command, NVMe(G3) IP and SSD are not available and user needs to power off/on the system to rerun NVMe(G3) IP and SSD.

For safety shutdown, it is recommended to send Shutdown command to the SSD. When the SSD is powered down without Shutdown command, the total count of unsafe shutdowns is increased.

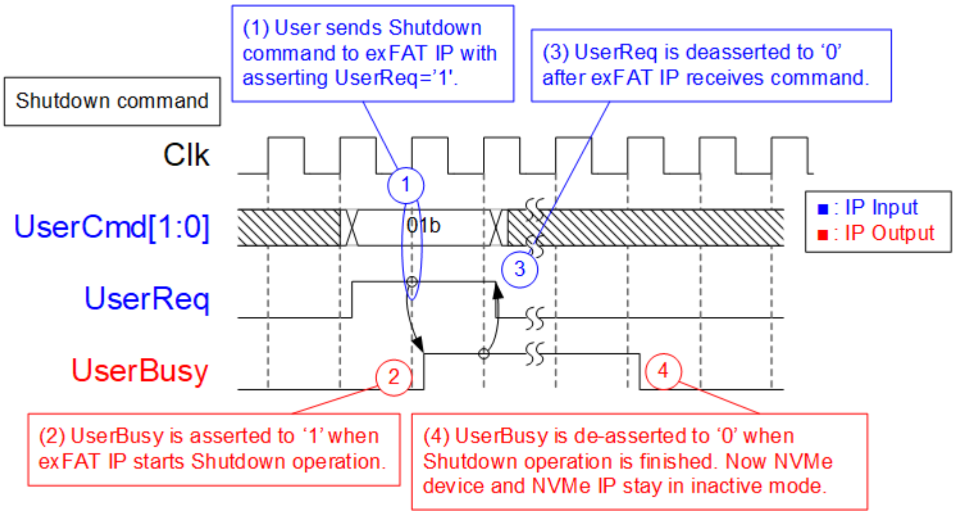
Shutdown command
(1) User sends Shutdown command to exFAT IP with asserting UserReq='1'.
(3) UserReq is deasserted to '0' after exFAT IP receives command.
Clk
UserCmd[1:0]
01b
UserReq
UserBusy
1
2
3
4
■ : IP Input
■ : IP Output
(2) UserBusy is asserted to '1' when exFAT IP starts Shutdown operation.
(4) UserBusy is de-asserted to '0' when Shutdown operation is finished. Now NVMe device and NVMe IP stay in inactive mode.

Figure 6: Timing diagram of Shutdown command

The example steps of command interface to run Shutdown command are as follows.

1) Set UserCmd = 01b (Shutdown) with asserting UserReq to '1'.
2) exFAT IP asserts UserBusy to '1' and starts Shutdown command operation.
3) UserReq is de-asserted to '0' to complete the current request. Then, user logic waits until Shutdown operation is finished by monitoring UserBusy.
4) UserBusy is de-asserted to '0' after finishing Shutdown command. The system can be powered down without data lost problem.

Write File command

To operate Write file command, user sets the input parameters of Write file command to control interface of exFAT IP and then data is read from user logic by exFAT IP via data interface.

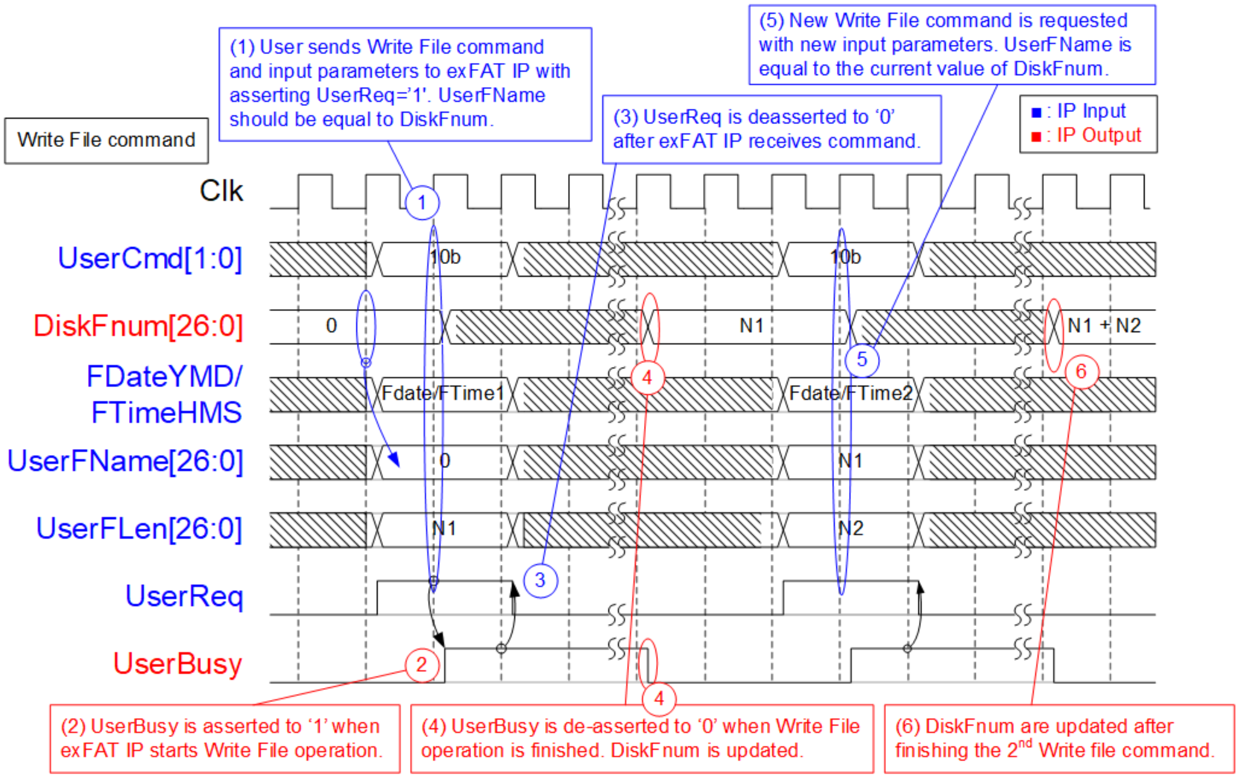
Write File command
(1) User sends Write File command and input parameters to exFAT IP with asserting UserReq='1'. UserFName should be equal to DiskFnum.
(5) New Write File command is requested with new input parameters. UserFName is equal to the current value of DiskFnum.
(3) UserReq is deasserted to '0' after exFAT IP receives command.
■ : IP Input
■ : IP Output
Clk
UserCmd[1:0]
DiskFnum[26:0]
FDateYMD/
FTimeHMS
UserFName[26:0]
UserFLen[26:0]
UserReq
UserBusy
10b
0
N1
N1 + N2
Fdate/FTime1
Fdate/FTime2
0
N1
N1
N2
1
2
3
4
5
6
(2) UserBusy is asserted to '1' when exFAT IP starts Write File operation.
(4) UserBusy is de-asserted to '0' when Write File operation is finished. DiskFnum is updated.
(6) DiskFnum are updated after finishing the 2nd Write file command.

Figure 7: Timing diagram of control interface during Write file command

The example steps of control interface to run Write file command are as follows.

1) User sets UserCmd = 10b (Write File), FDate (created date), FTime (created time), UserFName (the first file name to write), and UserFLen (total amount of written files) with asserting UserReq to '1'. UserFName should be equal to DiskFnum to create new file name which is the next value from the latest name. UserFLen must not be more than TotalFCap - UserFName. As shown in Figure 7, UserFName is equal to 0 when running the first Write file command to empty device. *Note: If the new file name is more than DiskFnum, it is maloperation and the new file is not found in the device.*
2) exFAT IP asserts UserBusy to '1' and starts Write file command operation by using the input parameters.
3) UserReq is de-asserted to '0' to complete the current request. Then, user logic waits until Write file operation is finished by monitoring UserBusy. In Write file operation, the data interface of exFAT IP forwards data from user logic to store in NVMe SSD via NVMe(G3) IP.
4) UserBusy is de-asserted to '0' after finishing forwarding total data and file header is created. DiskFnum is updated to be equal to UserFName + UserFLen. Created date and created time of the new file are equal to FDataYMD and FTimeHMS input.

5) UserFName of the next Write file command should be equal to DiskFnum which has been updated from the previous Write file command. FDate and FTime of the new Write file command can be changed.
6) DiskFnum is increased to show total amount of files in the device after finishing Write file command. In the example, the last value of DiskFnum is equal to N1 (UserFLen of the 1st Write file command) + N2 (UserFLen of the 2nd Write file command).

Assumed that N1+N2 is less than DirCap (one directory can store all new files in the 1st and 2nd Write file command), the new file in the device is created within the same directory, as shown in Figure 8. The 1st file name is 0000000.BIN and the last file name is (N1 + N2 - 1).BIN. Total digit of file name is fixed to 7, so 0 digit is filled as a prefix of filename in the device.

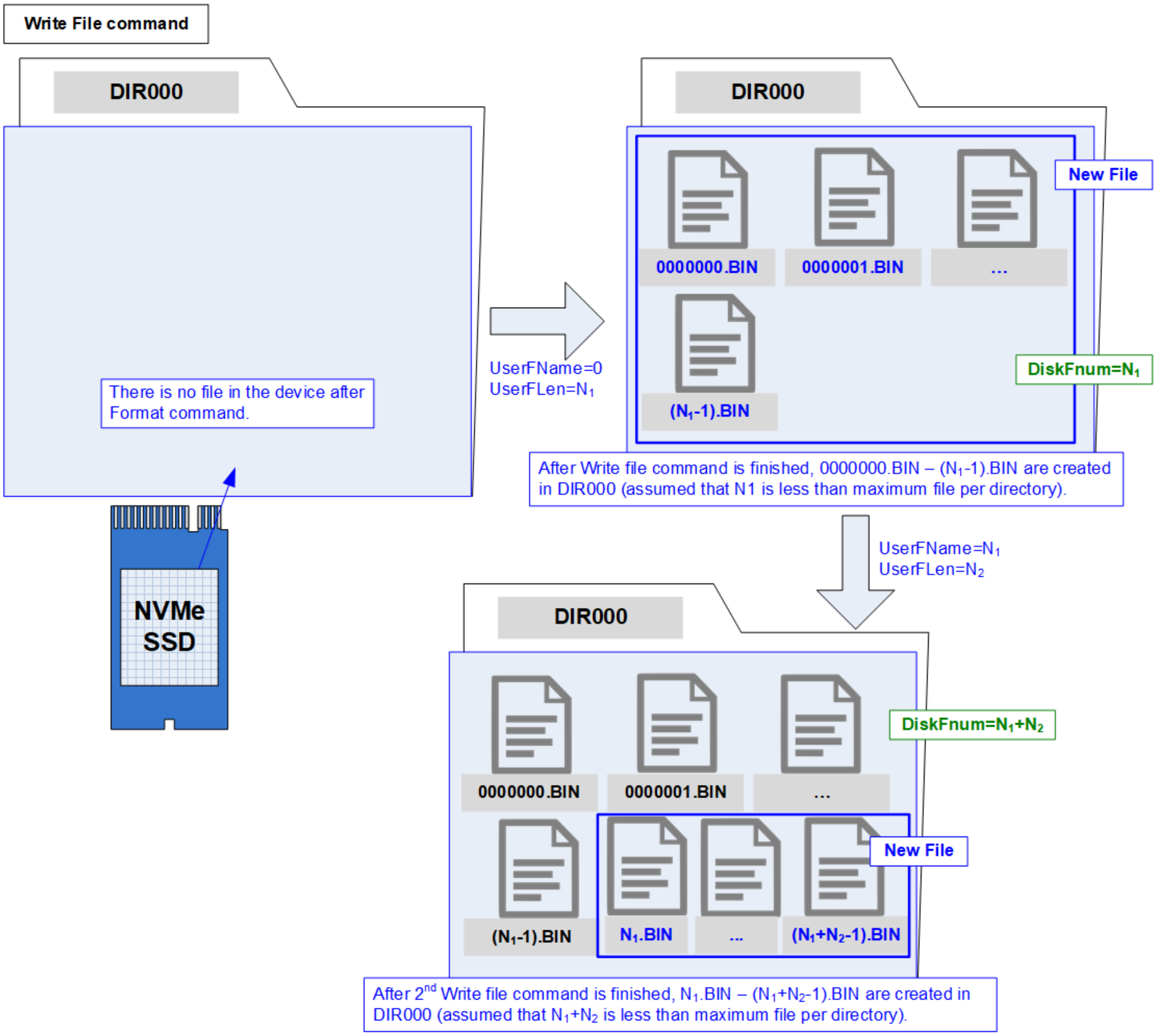
Write File command
DIR000
There is no file in the device after Format command.
NVMe SSD
UserFName=0
UserFLen=N₁
DIR000
0000000.BIN
0000001.BIN
...
(N₁-1).BIN
New File
DiskFnum=N₁
After Write file command is finished, 0000000.BIN – (N₁-1).BIN are created in DIR000 (assumed that N1 is less than maximum file per directory).
UserFName=N₁
UserFLen=N₂
DIR000
0000000.BIN
0000001.BIN
...
(N₁-1).BIN
N₁.BIN
...
(N₁+N₂-1).BIN
New File
DiskFnum=N₁+N₂
After 2nd Write file command is finished, N₁.BIN – (N₁+N₂-1).BIN are created in DIR000 (assumed that N₁+N₂ is less than maximum file per directory).

Figure 8: New file is created in the device after finishing Write file command

After exFAT IP receives Write file command request from user, the next process is transferring data from user logic to NVMe(G3) IP.

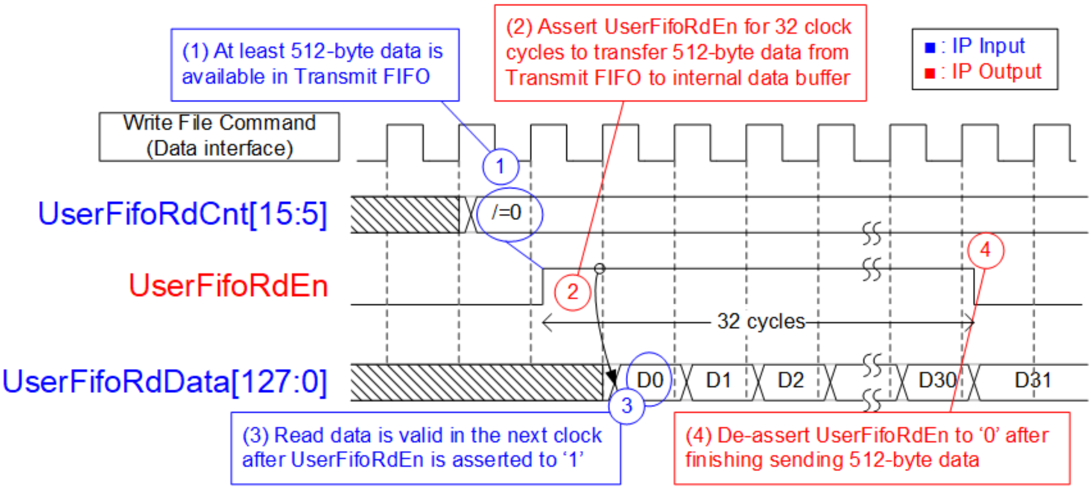
(1) At least 512-byte data is available in Transmit FIFO
(2) Assert UserFifoRdEn for 32 clock cycles to transfer 512-byte data from Transmit FIFO to internal data buffer
■ : IP Input
■ : IP Output
Write File Command (Data interface)
UserFifoRdCnt[15:5]
/=0
UserFifoRdEn
32 cycles
UserFifoRdData[127:0]
D0
D1
D2
D30
D31
1
2
3
4
(3) Read data is valid in the next clock after UserFifoRdEn is asserted to '1'
(4) De-assert UserFifoRdEn to '0' after finishing sending 512-byte data

Figure 9: TX FIFO Interface for Write file command

Figure 9 shows timing diagram of data interface during Write file command operation.

1) Before running a new burst write, UserFifoRdCnt[15:5] is monitored. The IP waits until at least 512-byte data is available in Transmit FIFO (UserFifoRdCnt[15:5] is not equal to 0).
2) Assert UserFifoRdEn to '1' for 32 clock cycles to read 512-byte data from Transmit FIFO.
3) UserFifoRdData is valid in the next clock after asserting UserFifoRdEn to '1'. 32 data are read continuously.
4) UserFifoRdEn is deasserted to '0' after reading the 32th data. If total data is not completely transferred, the IP goes back to step 1) for transferring the next 512-byte data. Otherwise, the IP changes to the Idle state.

Total data size for one command depends on UserFLen and File size. When UserFLen = N1, total amount of 128-bit data is equal to N1 x (File size in byte unit / 16).

Read File command

To operate Read file command, user sets the input parameters of Read file command to the control interface of exFAT IP. The inputs for Read File command are UserFName and UserFLen. After that, data is sent by exFAT IP to user logic via the data interface.

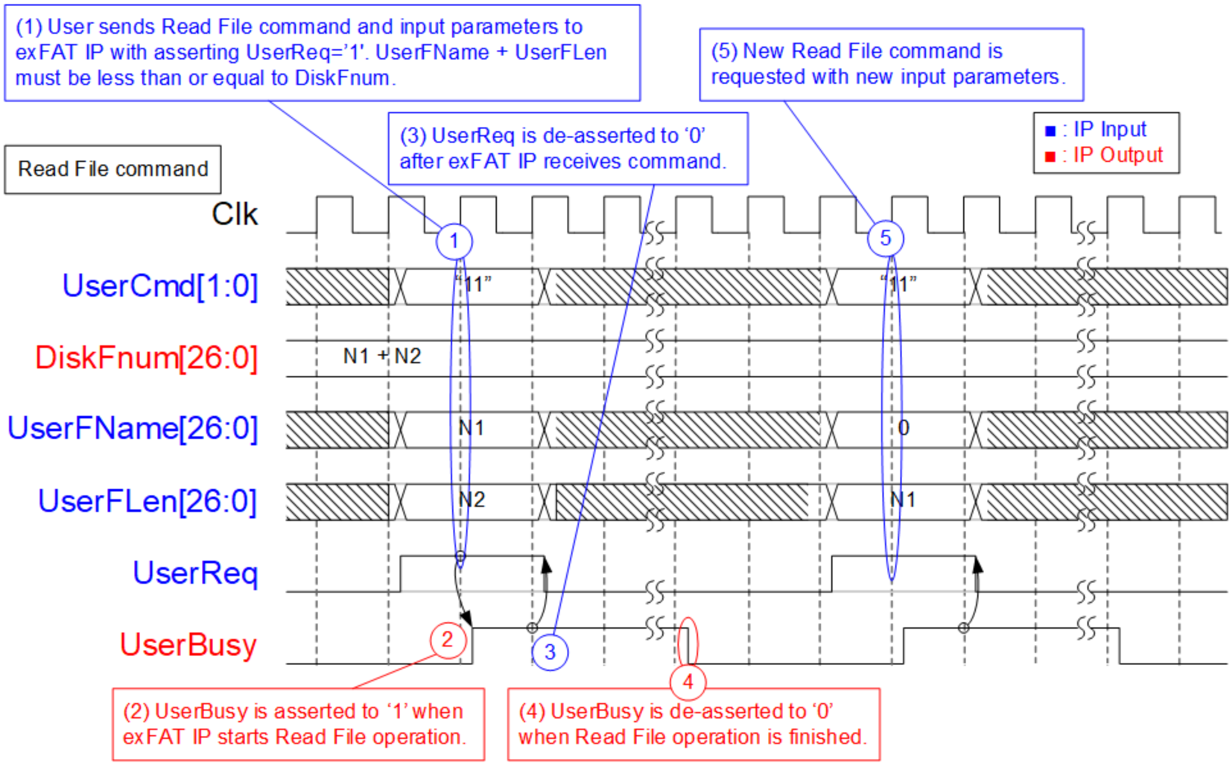
(1) User sends Read File command and input parameters to exFAT IP with asserting UserReq='1'. UserFName + UserFLen must be less than or equal to DiskFnum.
(5) New Read File command is requested with new input parameters.
(3) UserReq is de-asserted to '0' after exFAT IP receives command.
■ : IP Input
■ : IP Output
Read File command
Clk
UserCmd[1:0]
DiskFnum[26:0]
UserFName[26:0]
UserFLen[26:0]
UserReq
UserBusy
"11"
N1 + N2
N1
N2
"11"
0
N1
1
2
3
4
5
(2) UserBusy is asserted to '1' when exFAT IP starts Read File operation.
(4) UserBusy is de-asserted to '0' when Read File operation is finished.

Figure 10: Timing diagram of control interface during Read file command

The example steps of control interface to run Read file command are as follows.

1) User sets UserCmd = 11b (Read File), UserFName (the first file name to read), and UserFLen (total amount of read files) with asserting UserReq to '1'. The caution point is UserFName + UserFLen must be less than or equal to DiskFnum (total amount of files in the device).
2) exFAT IP asserts UserBusy to '1' and starts Read file command operation by using the input parameters.
3) UserReq is de-asserted to '0' to complete the current request. Then, user logic waits until Read file operation is finished by monitoring UserBusy. In this step, the data interface of exFAT IP forwards read data from NVMe SSD to user logic via NVMe(G3) IP.
4) UserBusy is de-asserted to '0' after finishing forwarding total data. DiskFnum is stable during Read file operation.
5) User can send the new command request to exFAT IP.

Data interface to transfer data from the device to user logic is displayed on Figure 11.

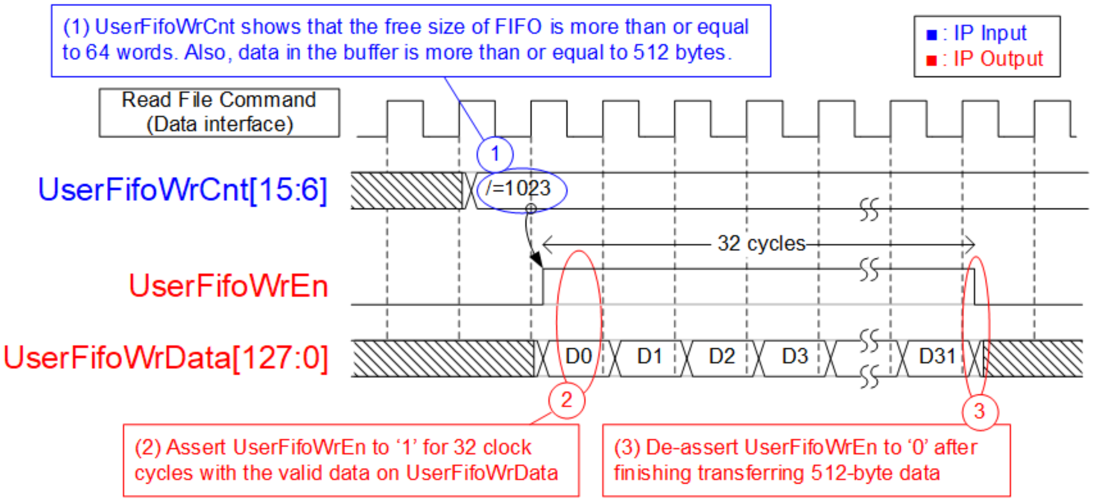
(1) UserFifoWrCnt shows that the free size of FIFO is more than or equal to 64 words. Also, data in the buffer is more than or equal to 512 bytes.
■ : IP Input
■ : IP Output
Read File Command (Data interface)
UserFifoWrCnt[15:6]
/=1023
1
32 cycles
UserFifoWrEn
UserFifoWrData[127:0]
D0
D1
D2
D3
D31
2
3
(2) Assert UserFifoWrEn to '1' for 32 clock cycles with the valid data on UserFifoWrData
(3) De-assert UserFifoWrEn to '0' after finishing transferring 512-byte data

Figure 11: RX FIFO Interface for Read file command

For Read file command, UserFifoWrEn is asserted to '1' with the valid value of UserFifoWrData to send data to the user via FIFO interface.

1) Before starting a new burst transfer, UserFifoWrCnt[15:6] is monitored. The IP waits until the free space of Received FIFO is much enough (UserFifoWrCnt[15:6] is not equal to all 1 or 1023).
2) Assert UserFifoWrEn to '1' for 32 clock cycles to transfer 512-byte data from NVMe(G3) IP to user.
3) After transferring 512-byte data, UserFifoWrEn is de-asserted to '0'. If total data is not completely transferred, the IP returns to step 1) to check FIFO status and the amount of received data from SSD for transferring the next 512-byte data.

Similar to Write file command, total amount of 128-bit data is equal to UserFLen x (File size in byte unit / 16).

Error

UserError is asserted to ‘1’ by error condition within NVMe(G3) IP or exFAT IP. The details of error status are monitored by UserErrorType. To clear Error flag, user needs to assert reset signal (RstB=’0’) to exFAT IP and NVMe(G3) IP.

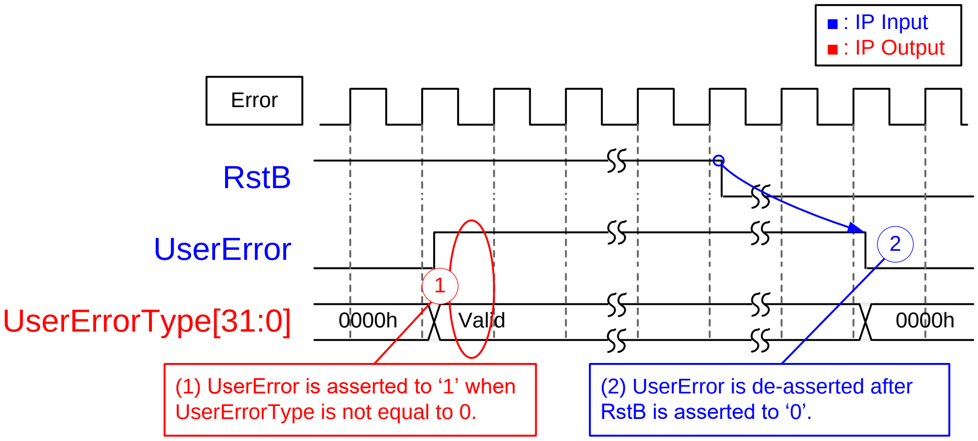
■ : IP Input
■ : IP Output
Error
RstB
UserError
UserErrorType[31:0]
0000h
Valid
0000h
1
2
(1) UserError is asserted to ‘1’ when UserErrorType is not equal to 0.
(2) UserError is de-asserted after RstB is asserted to ‘0’.

Figure 12: Error flag timing diagram

Limitation

(1) NVMe device which is connected to exFAT IP must be formatted by exFAT IP. The maloperation will be happened such as wrong device information (TotalFCap, DiskFsize, and DiskFnum) if the device is not formatted by exFAT IP.

(2) All files in NVMe device must be written by exFAT IP. The maloperation will be happened in the system if the device includes some files which is written by the other hosts.

(3) The other hosts is allowed to access NVMe device by read-only mode.

(4) All files in NVMe device have the same size, defined by FSize during Format command. To change FSize value, the device must be formatted again with new FSize value.

(5) Table 3 shows the maximum amount of files to store in one directory which depends on device capacity. The equation to calculate directory name which stores the file from filename is as follows.
DIR Name = (<FileName>/DirCap) – 1
Assumed that device capacity is 100 GB, DirCap (the maximum amount of file in one directory) is equal to 512.
0000000.BIN – 000001FF.BIN are stored to DIR000.
0000200.BIN – 000003FF.BIN are stored to DIR001.
0000400.BIN – 000005FF.BIN are stored to DIR002.
0000600.BIN – 000007FF.BIN are stored to DIR003.
0000800.BIN – 000009FF.BIN are stored to DIR004.
0000A00.BIN – 00000BFF.BIN are stored to DIR005.
0000C00.BIN – 00000DFF.BIN are stored to DIR006.
0000E00.BIN – 00000FFF.BIN are stored to DIR007.
DIR008 – DIR1FF are empty directories.

(6) In Write file command, UserFName input should be equal to DiskFnum.

a) If UserFName is more than DiskFnum, it is the error condition. After running by this condition, the new file is not found in the device and DiskFnum value is not correct.

b) If UserFName is less than DiskFnum, the old file is replaced by the new data. DiskFnum does not change if the sum of UserFName and UserFlen in the new write request is less than the current value of DiskFnum. DiskFnum to show total amount of files in the device is not reduced without running Format command.

Verification Methods

The exFAT-IP Core for NVMe functionality was verified by simulation and also proved on real board design by using KCU105, ZCU102, ZCU106 and VCU118 board.

Recommended Design Experience

Experience design engineers with a knowledge of Vivado Tools should easily integrate this IP into their design.

Ordering Information

This product is available directly from Design Gateway Co., Ltd. Please contact Design Gateway Co., Ltd. for pricing and additional information about this product using the contact information on the front page of this datasheet.

Revision History

Revision	Date	Description
1.0	11-Jan-2019	Initial Release
1.1	22-Mar-2019	Add DiskFsize and DiskFnum input
1.2	10-May-2019	Update the maximum amount of files per directory
1.3	18-Feb-2020	Support VCU118
1.4	23-Jul-2020	Support ZCU106
1.5	15-Dec-2020	Update company info
1.6	14-Mar-2022	Support NVMeG3-IP