

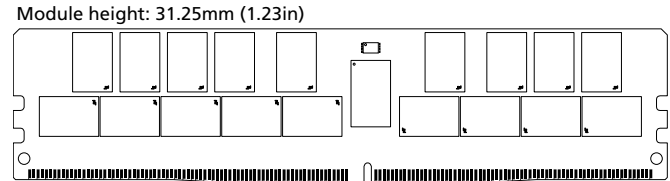
DDR4 SDRAM LRDIMM

MTA72ASS8G72LZ – 64GB

Features

- DDR4 functionality and operations supported as defined in the component data sheet
- 288-pin, command/address/control-registered, data-buffered, load-reduced dual in-line memory module (LRDIMM)
- Fast data transfer rates: PC4-2933, PC4-2666, or PC4-2400
- 64GB (8 Gig x 72)
- $V_{DD} = 1.20V$ (NOM)
- $V_{PP} = 2.5V$ (NOM)
- $V_{DDSPD} = 2.5V$ (NOM)
- Supports ECC error detection and correction
- Nominal and dynamic on-die termination (ODT) for data, strobe, and mask signals
- Low-power auto self refresh (LPASR)
- On-die internal, adjustable V_{REFDQ} generation
- Quad-rank, using 16Gb TwinDie™ DDR4
- On-board I²C temperature sensor with integrated serial presence-detect (SPD) EEPROM
- 16 internal banks; 4 groups of 4 banks each
- Fixed burst chop (BC) of 4 and burst length (BL) of 8 via the mode register set (MRS)
- Selectable BC4 or BL8 on-the-fly (OTF)
- Gold edge contacts
- Halogen-free
- Fly-by topology
- Multiplexed command and address bus
- Terminated control, command, and address bus

Figure 1: 288-Pin LRDIMM (MO-309, R/C-E2)



Options

- Operating temperature
 - Commercial ($0^{\circ}C \leq T_{OPER} \leq 95^{\circ}C$)
- Package
 - 288-pin DIMM (halogen-free)
- Frequency/CAS latency
 - 0.682ns @ CL = 21 (DDR4-2933)
 - 0.75ns @ CL = 19 (DDR4-2666)
 - 0.83ns @ CL = 17 (DDR4-2400)

Marking

- Operating temperature: None
- Package: Z
- Frequency/CAS latency: -2G9, -2G6, -2G3

Table 1: Key Timing Parameters

Speed Grade	PC4-	Data Rate (MT/s)														t _{RCD} (ns)	t _{RP} (ns)	t _{RC} (ns)
		CL =																
		24	22/21	20	19	18	17	16	15	14	13	12	11	10	9			
-3G2	3200	3200	3200/-	2666	2666	2400	2400	2133	2133	1866	1866	1600	1600	1333	-	13.75	13.75	45.75
-2G9	2933	-	2933/2933	2666	2666	2400	2400	2133	2133	1866	1866	1600	1600	1333	-	14.32	14.32	46.32



Table 1: Key Timing Parameters (Continued)

Speed Grade	PC4-	Data Rate (MT/s) CL =														t _{RCD} (ns)	t _{RP} (ns)	t _{RC} (ns)
		24	22/21	20	19	18	17	16	15	14	13	12	11	10	9			
-2G6	2666	-	-	2666	2666	2400	2400	2133	2133	1866	1866	1600	1600	1333	-	14.16	14.16	46.16
-2G3	2400	-	-	-	-	2400	2400	2133	2133	1866	1866	1600	1600	1333	-	14.16	14.16	46.16
-2G1	2133	-	-	-	-	-	-	2133	2133	1866	1866	1600	1600	1333	1333	13.5	13.5	46.5

Table 2: Addressing

Parameter	64GB
Row address	128K A[16:0]
Column address	1K A[9:0]
Device bank group address	4 BG[1:0]
Device bank address per group	4 BA[1:0]
Device configuration	16Gb TwinDie (4 Gig x 4), 16 banks
Module rank address	4 CS_n[3:0]

Table 3: Part Numbers and Timing Parameters – 64GB Modules

Base device: MT40A4G4,¹ 16Gb TwinDie DDR4 SDRAM

Part Number ²	Module Density	Configuration	Module Bandwidth	Memory Clock/ Data Rate	Clock Cycles (CL-t _{RCD} -t _{RP})
MTA72ASS8G72LZ-2G9__	64GB	8 Gig x 72	23.47 GB/s	0.682ns/2933 MT/s	21-21-21
MTA72ASS8G72LZ-2G6__	64GB	8 Gig x 72	21.3 GB/s	0.75ns/2666 MT/s	19-19-19
MTA72ASS8G72LZ-2G3__	64GB	8 Gig x 72	19.2 GB/s	0.83ns/2400 MT/s	17-17-17

- Notes: 1. The data sheet for the base device can be found on micron.com.
 2. All part numbers end with a two-place code (not shown) that designates component and PCB revisions. Consult factory for current revision codes. Example: MTA72ASS8G72LZ-2G9D1.

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Pin Assignments

Table 4: Pin Assignments

288-Pin DDR4 LRDIMM Front								288-Pin DDR4 LRDIMM Back							
Pin	Symbol	Pin	Symbol	Pin	Symbol	Pin	Symbol	Pin	Symbol	Pin	Symbol	Pin	Symbol	Pin	Symbol
1	NC	37	V _{SS}	73	V _{DD}	109	V _{SS}	145	NC	181	DQ29	217	V _{DD}	253	DQ41
2	V _{SS}	38	DQ24	74	CK0_t	110	DQS14_t	146	V _{REFCA}	182	V _{SS}	218	CK1_t	254	V _{SS}
3	DQ4	39	V _{SS}	75	CK0_c	111	DQS14_c	147	V _{SS}	183	DQ25	219	CK1_c	255	DQS5_c
4	V _{SS}	40	DQS12_t	76	V _{DD}	112	V _{SS}	148	DQ5	184	V _{SS}	220	V _{DD}	256	DQS5_t
5	DQ0	41	DQS12_c	77	V _{TT}	113	DQ46	149	V _{SS}	185	DQS3_c	221	V _{TT}	257	V _{SS}
6	V _{SS}	42	V _{SS}	78	EVENT_n	114	V _{SS}	150	DQ1	186	DQS3_t	222	PARITY	258	DQ47
7	DQS9_t	43	DQ30	79	A0	115	DQ42	151	V _{SS}	187	V _{SS}	223	V _{DD}	259	V _{SS}
8	DQS09_c	44	V _{SS}	80	V _{DD}	116	V _{SS}	152	DQS0_c	188	DQ31	224	BA1	260	DQ43
9	V _{SS}	45	DQ26	81	BA0	117	DQ52	153	DQS0_t	189	V _{SS}	225	A10_AP	261	V _{SS}
10	DQ6	46	V _{SS}	82	RAS_n/ A16	118	V _{SS}	154	V _{SS}	190	DQ27	226	V _{DD}	262	DQ53
11	V _{SS}	47	CB4	83	V _{DD}	119	DQ48	155	DQ7	191	V _{SS}	227	NC	263	V _{SS}
12	DQ2	48	V _{SS}	84	S0_n	120	V _{SS}	156	V _{SS}	192	CB5	228	WE_n/ A14	264	DQ49
13	V _{SS}	49	CB0	85	V _{DD}	121	DQS15_t	157	DQ3	193	V _{SS}	229	V _{DD}	265	V _{SS}
14	DQ12	50	V _{SS}	86	CAS_n/ A15	122	DQS15_c	158	V _{SS}	194	CB1	230	NC	266	DQS6_c
15	V _{SS}	51	DQS17_t	87	ODT0	123	V _{SS}	159	DQ13	195	V _{SS}	231	V _{DD}	267	DQS6_t
16	DQ8	52	DQS17_c	88	V _{DD}	124	DQ54	160	V _{SS}	196	DQS8_c	232	A13	268	V _{SS}
17	V _{SS}	53	V _{SS}	89	S1_n	125	V _{SS}	161	DQ9	197	DQS8_t	233	V _{DD}	269	DQ55
18	DQS10_t	54	CB6	90	V _{DD}	126	DQ50	162	V _{SS}	198	V _{SS}	234	A17	270	V _{SS}
19	DQS10_c	55	V _{SS}	91	ODT1	127	V _{SS}	163	DQS1_c	199	CB7	235	NF	271	DQ51
20	V _{SS}	56	CB2	92	V _{DD}	128	DQ60	164	DQS1_t	200	V _{SS}	236	V _{DD}	272	V _{SS}
21	DQ14	57	V _{SS}	93	S2_n	129	V _{SS}	165	V _{SS}	201	CB3	237	S3_n	273	DQ61
22	V _{SS}	58	RESET_n	94	V _{SS}	130	DQ56	166	DQ15	202	V _{SS}	238	SA2	274	V _{SS}
23	DQ10	59	V _{DD}	95	DQ36	131	V _{SS}	167	V _{SS}	203	CKE1	239	V _{SS}	275	DQ57
24	V _{SS}	60	CKE0	96	V _{SS}	132	DQS16_t	168	DQ11	204	V _{DD}	240	DQ37	276	V _{SS}
25	DQ20	61	V _{DD}	97	DQ32	133	DQS16_c	169	V _{SS}	205	NC	241	V _{SS}	277	DQS7_c
26	V _{SS}	62	ACT_n	98	V _{SS}	134	V _{SS}	170	DQ21	206	V _{DD}	242	DQ33	278	DQS7_t
27	DQ16	63	BG0	99	DQS13_t	135	DQ62	171	V _{SS}	207	BG1	243	V _{SS}	279	V _{SS}
28	V _{SS}	64	V _{DD}	100	DQS13_c	136	V _{SS}	172	DQ17	208	ALERT_n	244	DQS4_c	280	DQ63
29	DQS11_t	65	A12	101	V _{SS}	137	DQ58	173	V _{SS}	209	V _{DD}	245	DQS4_t	281	V _{SS}
30	DQS11_c	66	A9	102	DQ38	138	V _{SS}	174	DQS2_c	210	A11	246	V _{SS}	282	DQ59
31	V _{SS}	67	V _{DD}	103	V _{SS}	139	SA0	175	DQS2_t	211	A7	247	DQ39	283	V _{SS}
32	DQ22	68	A8	104	DQ34	140	SA1	176	V _{SS}	212	V _{DD}	248	V _{SS}	284	V _{DDSPD}
33	V _{SS}	69	A6	105	V _{SS}	141	SCL	177	DQ23	213	A5	249	DQ35	285	SDA
34	DQ18	70	V _{DD}	106	DQ44	142	V _{PP}	178	V _{SS}	214	A4	250	V _{SS}	286	V _{PP}
35	V _{SS}	71	A3	107	V _{SS}	143	V _{PP}	179	DQ19	215	V _{DD}	251	DQ45	287	V _{PP}
36	DQ28	72	A1	108	DQ40	144	NC	180	V _{SS}	216	A2	252	V _{SS}	288	V _{PP}

Pin Descriptions

The pin description table below is a comprehensive list of all possible pins for DDR4 modules. All pins listed may not be supported on this module. See Functional Block Diagram for pins specific to this module.

Table 5: Pin Descriptions

Symbol	Type	Description
Ax	Input	Address inputs: Provide the row address for ACTIVATE commands and the column address for READ/WRITE commands in order to select one location out of the memory array in the respective bank (A10/AP, A12/BC_n, WE_n/A14, CAS_n/A15, and RAS_n/A16 have additional functions; see individual entries in this table). The address inputs also provide the op-code during the MODE REGISTER SET command. A17 is only defined for x4 SDRAM.
A10/AP	Input	Auto precharge: A10 is sampled during READ and WRITE commands to determine whether an auto precharge should be performed on the accessed bank after a READ or WRITE operation (HIGH = auto precharge; LOW = no auto precharge). A10 is sampled during a PRECHARGE command to determine whether the precharge applies to one bank (A10 LOW) or all banks (A10 HIGH). If only one bank is to be precharged, the bank is selected by the bank group and bank addresses.
A12/BC_n	Input	Burst chop: A12/BC_n is sampled during READ and WRITE commands to determine if burst chop (on-the-fly) will be performed (HIGH = no burst chop; LOW = burst chopped). See Command Truth Table in the DDR4 component data sheet.
ACT_n	Input	Command input: ACT_n defines the ACTIVATE command being entered along with CS_n. The input into RAS_n/A16, CAS_n/A15, and WE_n/A14 are considered as row address A16, A15, and A14. See Command Truth Table.
BAx	Input	Bank address inputs: Define the bank (with a bank group) to which an ACTIVATE, READ, WRITE, or PRECHARGE command is being applied. Also determine which mode register is to be accessed during a MODE REGISTER SET command.
BGx	Input	Bank group address inputs: Define the bank group to which a REFRESH, ACTIVATE, READ, WRITE, or PRECHARGE command is being applied. Also determine which mode register is to be accessed during a MODE REGISTER SET command. BG[1:0] are used in the x4 and x8 configurations. x16-based SDRAM only has BG0.
C0, C1, C2 (RDIMM/LRDIMM only)	Input	Chip ID: These inputs are used only when devices are stacked; that is, 2H, 4H, and 8H stacks for x4 and x8 configurations using through-silicon vias (TSVs). These pins are not used in the x16 configuration. Some DDR4 modules support a traditional DDP package, which uses CS1_n, CKE1, and ODT1 to control the second die. All other stack configurations, such as a 4H or 8H, are assumed to be single-load (master/slave) type configurations where C0, C1, and C2 are used as chip ID selects in conjunction with a single CS_n, CKE, and ODT. Chip ID is considered part of the command code.
CKx_t CKx_c	Input	Clock: Differential clock inputs. All address, command, and control input signals are sampled on the crossing of the positive edge of CK_t and the negative edge of CK_c.
CKEx	Input	Clock enable: CKE HIGH activates and CKE LOW deactivates the internal clock signals, device input buffers, and output drivers. Taking CKE LOW provides PRECHARGE POWER-DOWN and SELF REFRESH operations (all banks idle), or active power-down (row active in any bank). CKE is asynchronous for self refresh exit. After V _{REFCA} has become stable during the power-on and initialization sequence, it must be maintained during all operations (including SELF REFRESH). CKE must be maintained HIGH throughout read and write accesses. Input buffers (excluding CK_t, CK_c, ODT, RESET_n, and CKE) are disabled during power-down. Input buffers (excluding CKE and RESET_n) are disabled during self refresh.
CSx_n	Input	Chip select: All commands are masked when CS_n is registered HIGH. CS_n provides external rank selection on systems with multiple ranks. CS_n is considered part of the command code (CS2_n and CS3_n are not used on UDIMMs).

Table 5: Pin Descriptions (Continued)

Symbol	Type	Description
ODTx	Input	On-die termination: ODT (registered HIGH) enables termination resistance internal to the DDR4 SDRAM. When enabled, ODT (R_{TT}) is applied only to each DQ, DQS _t , DQS _c , DM _n /DBI _n /TDQS _t , and TDQS _c signal for x4 and x8 configurations (when the TDQS function is enabled via the mode register). For the x16 configuration, R_{TT} is applied to each DQ, DQSU _t , DQSU _c , DQSL _t , DQSL _c , UDM _n , and LDM _n signal. The ODT pin will be ignored if the mode registers are programmed to disable R_{TT} .
PARITY	Input	Parity for command and address: This function can be enabled or disabled via the mode register. When enabled in MR5, the DRAM calculates parity with ACT _n , RAS _n /A16, CAS _n /A15, WE _n /A14, BG[1:0], BA[1:0], A[16:0]. Input parity should be maintained at the rising edge of the clock and at the same time as command and address with CS _n LOW.
RAS _n /A16 CAS _n /A15 WE _n /A14	Input	Command inputs: RAS _n /A16, CAS _n /A15, and WE _n /A14 (along with CS _n) define the command and/or address being entered and have multiple functions. For example, for activation with ACT _n LOW, these are addresses like A16, A15, and A14, but for a non-activation command with ACT _n HIGH, these are command pins for READ, WRITE, and other commands defined in Command Truth Table.
RESET _n	CMOS Input	Active LOW asynchronous reset: Reset is active when RESET _n is LOW and inactive when RESET _n is HIGH. RESET _n must be HIGH during normal operation.
SAX	Input	Serial address inputs: Used to configure the temperature sensor/SPD EEPROM address range on the I ² C bus.
SCL	Input	Serial clock for temperature sensor/SPD EEPROM: Used to synchronize communication to and from the temperature sensor/SPD EEPROM on the I ² C bus.
DQx, CBx	I/O	Data input/output and check bit input/output: Bidirectional data bus. DQ represents DQ[3:0], DQ[7:0], and DQ[15:0] for the x4, x8, and x16 configurations, respectively. If cyclic redundancy checksum (CRC) is enabled via the mode register, the CRC code is added at the end of the data burst. Any one or all of DQ0, DQ1, DQ2, or DQ3 may be used for monitoring of internal V_{REF} level during test via mode register setting MR[4] A[4] = HIGH; training times change when enabled.
DM _n /DBI _n / TDQS _t (DMU _n , DBIU _n), (DML _n / DBII _n)	I/O	Input data mask and data bus inversion: DM _n is an input mask signal for write data. Input data is masked when DM _n is sampled LOW coincident with that input data during a write access. DM _n is sampled on both edges of DQS. DM is multiplexed with the DBI function by the mode register A10, A11, and A12 settings in MR5. For a x8 device, the function of DM or TDQS is enabled by the mode register A11 setting in MR1. DBI _n is an input/output identifying whether to store/output the true or inverted data. If DBI _n is LOW, the data will be stored/output after inversion inside the DDR4 device and not inverted if DBI _n is HIGH. TDQS is only supported in x8 SDRAM configurations (TDQS is not valid for UDIMMs).
SDA	I/O	Serial Data: Bidirectional signal used to transfer data in or out of the EEPROM or EEPROM/TS combo device.
DQS _t DQS _c DQSU _t DQSU _c DQSL _t DQSL _c	I/O	Data strobe: Output with read data, input with write data. Edge-aligned with read data, centered-aligned with write data. For x16 configurations, DQSL corresponds to the data on DQ[7:0], and DQSU corresponds to the data on DQ[15:8]. For the x4 and x8 configurations, DQS corresponds to the data on DQ[3:0] and DQ[7:0], respectively. DDR4 SDRAM supports a differential data strobe only and does not support a single-ended data strobe.
ALERT _n	Output	Alert output: Possesses functions such as CRC error flag and command and address parity error flag as output signal. If a CRC error occurs, ALERT _n goes LOW for the period time interval and returns HIGH. If an error occurs during a command address parity check, ALERT _n goes LOW until the on-going DRAM internal recovery transaction is complete. During connectivity test mode, this pin functions as an input. Use of this signal is system-dependent. If not connected as signal, ALERT _n pin must be connected to V_{DD} on DIMMs.
EVENT _n	Output	Temperature event: The EVENT _n pin is asserted by the temperature sensor when critical temperature thresholds have been exceeded. This pin has no function (NF) on modules without temperature sensors.

Table 5: Pin Descriptions (Continued)

Symbol	Type	Description
TDQS_t TDQS_c (x8 DRAM-based RDIMM only)	Output	Termination data strobe: When enabled via the mode register, the DRAM device enables the same R_{TT} termination resistance on TDQS_t and TDQS_c that is applied to DQS_t and DQS_c. When the TDQS function is disabled via the mode register, the DM/TDQS_t pin provides the data mask (DM) function, and the TDQS_c pin is not used. The TDQS function must be disabled in the mode register for both the x4 and x16 configurations. The DM function is supported only in x8 and x16 configurations. DM, DBI, and TDQS are a shared pin and are enabled/disabled by mode register settings. For more information about TDQS, see the DDR4 DRAM component data sheet (TDQS_t and TDQS_c are not valid for UDIMMs).
V_{DD}	Supply	Module power supply: 1.2V (TYP).
V_{PP}	Supply	DRAM activating power supply: 2.5V $-0.125V$ / $+0.250V$.
V_{REFCA}	Supply	Reference voltage for control, command, and address pins.
V_{SS}	Supply	Ground.
V_{TT}	Supply	Power supply for termination of address, command, and control $V_{DD}/2$.
V_{DDSPD}	Supply	Power supply used to power the I ² C bus for SPD.
RFU	–	Reserved for future use.
NC	–	No connect: No internal electrical connection is present.
NF	–	No function: May have internal connection present, but has no function.



DQ Map

Table 6: Component-to-Module DQ Map, Front

Component Reference Number	Component DQ	Module DQ	Module Pin Number	Component Reference Number	Component DQ	Module DQ	Module Pin Number
U1	0	7	155	U2	0	15	166
	1	5	148		1	13	159
	2	6	10		2	14	21
	3	4	3		3	12	14
U3	0	23	177	U4	0	31	188
	1	21	170		1	29	181
	2	22	32		2	30	43
	3	20	25		3	28	36
U5	0	CB7	199	U7	0	39	247
	1	CB5	192		1	37	240
	2	CB6	54		2	38	102
	3	CB4	47		3	36	95
U8	0	47	258	U9	0	55	269
	1	45	251		1	53	262
	2	46	113		2	54	124
	3	44	106		3	52	117
U10	0	63	280	U12	0	2	12
	1	61	273		1	1	150
	2	62	135		2	3	157
	3	60	128		3	0	5
U13	0	8	16	U14	0	16	27
	1	10	23		1	18	34
	2	9	161		2	17	172
	3	11	168		3	19	179
U15	0	26	45	U16	0	CB2	56
	1	25	183		1	CB1	194
	2	27	190		2	CB3	201
	3	24	38		3	CB0	49
U17	0	34	104	U18	0	42	115
	1	32	97		1	40	108
	2	35	249		2	43	260
	3	33	242		3	41	253
U19	0	50	126	U20	0	56	130
	1	48	119		1	58	137
	2	51	271		2	57	275
	3	49	264		3	59	282

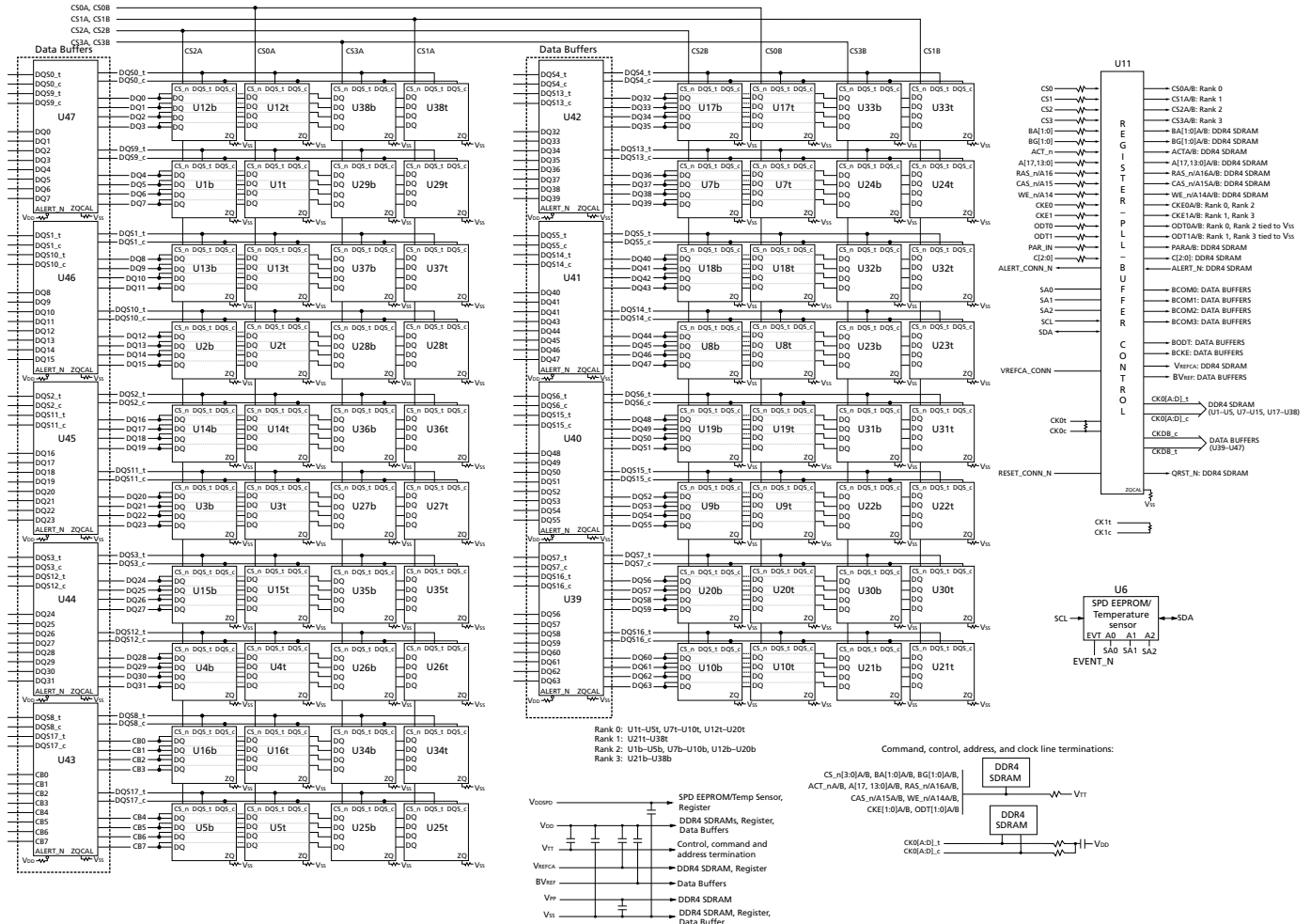


Table 7: Component-to-Module DQ Map, Back

Component Reference Number	Component DQ	Module DQ	Module Pin Number	Component Reference Number	Component DQ	Module DQ	Module Pin Number
U21	0	61	273	U22	0	53	262
	1	63	280		1	55	269
	2	60	128		2	52	117
	3	62	135		3	54	124
U23	0	45	251	U24	0	37	240
	1	47	258		1	39	247
	2	44	106		2	36	95
	3	46	113		3	38	102
U25	0	CB5	192	U26	0	29	181
	1	CB7	199		1	31	188
	2	CB4	47		2	28	36
	3	CB6	54		3	30	43
U27	0	21	170	U28	0	13	159
	1	23	177		1	15	166
	2	20	25		2	12	14
	3	22	32		3	14	21
U29	0	5	148	U30	0	58	137
	1	7	155		1	56	130
	2	4	3		2	59	282
	3	6	10		3	57	275
U31	0	48	119	U32	0	40	108
	1	50	126		1	42	115
	2	49	264		2	41	253
	3	51	271		3	43	260
U33	0	32	97	U34	0	CB1	194
	1	34	104		1	CB2	56
	2	33	242		2	CB0	49
	3	35	249		3	CB3	201
U35	0	25	183	U36	0	18	34
	1	26	45		1	16	27
	2	24	38		2	19	179
	3	27	190		3	17	172
U37	0	10	23	U38	0	1	150
	1	8	16		1	2	12
	2	11	168		2	0	5
	3	9	161		3	3	157

Functional Block Diagram

Figure 2: Functional Block Diagram



Note: 1. The ZQ ball on each DDR4 component is connected to an external $240\Omega \pm 1\%$ resistor that is tied to ground. It is used for the calibration of the component's ODT and output driver.

General Description

High-speed DDR4 SDRAM modules use DDR4 SDRAM devices with two or four internal memory bank groups. DDR4 SDRAM modules utilizing 4- and 8-bit-wide DDR4 SDRAM devices have four internal bank groups consisting of four memory banks each, providing a total of 16 banks. 16-bit-wide DDR4 SDRAM devices have two internal bank groups consisting of four memory banks each, providing a total of eight banks. DDR4 SDRAM modules benefit from DDR4 SDRAM's use of an $8n$ -prefetch architecture with an interface designed to transfer two data words per clock cycle at the I/O pins. A single READ or WRITE operation for the DDR4 SDRAM effectively consists of a single $8n$ -bit-wide, four-clock data transfer at the internal DRAM core and eight corresponding n -bit-wide, one-half-clock-cycle data transfers at the I/O pins.

DDR4 modules use two sets of differential signals: DQS_t and DQS_c to capture data and CK_t and CK_c to capture commands, addresses, and control signals. Differential clocks and data strobes ensure exceptional noise immunity for these signals and provide precise crossing points to capture input signals.

Fly-By Topology

DDR4 modules use faster clock speeds than earlier DDR technologies, making signal quality more important than ever. For improved signal quality, the clock, control, command, and address buses have been routed in a fly-by topology, where each clock, control, command, and address pin on each DRAM is connected to a single trace and terminated (rather than a tree structure, where the termination is off the module near the connector). Inherent to fly-by topology, the timing skew between the clock and DQS signals can be easily accounted for by using the write-leveling feature of DDR4.

Module Manufacturing Location

Micron Technology manufactures modules at sites world-wide. Customers may receive modules from any of the following manufacturing locations:

Table 8: DRAM Module Manufacturing Locations

Manufacturing Site Location	Country of Origin Specified on Label
Boise, USA	USA
Aguadilla, Puerto Rico	Puerto Rico
Xian, China	China
Singapore	Singapore

Address Mapping to DRAM

Address Mirroring

To achieve optimum routing of the address bus on DDR4 multi rank modules, the address bus will be wired as shown in the table below, or mirrored. For quad rank modules, ranks 1 and 3 are mirrored and ranks 0 and 2 are non-mirrored. Highlighted address pins have no secondary functions allowing for normal operation when cross-wired. Data is still read from the same address it was written. However, Load Mode operations require a specific address. This requires the controller to accommodate for a rank that is "mirrored." Systems may reference DDR4 SPD to determine if the module has mirroring implemented or not. See the JEDEC DDR4 SPD specification for more details.

Table 9: Address Mirroring

Edge Connector Pin	DRAM Pin, Non-mirrored	DRAM Pin, Mirrored
A0	A0	A0
A1	A1	A1
A2	A2	A2
A3	A3	A4
A4	A4	A3
A5	A5	A6
A6	A6	A5
A7	A7	A8
A8	A8	A7
A9	A9	A9
A10	A10	A10
A11	A11	A13
A13	A13	A11
A12	A12	A12
A14	A14	A14
A15	A15	A15
A16	A16	A16
A17	A17	A17
BA0	BA0	BA1
BA1	BA1	BA0
BG0	BG0	BG1
BG1	BG1	BG0

Registering Clock Driver Operation

Registered DDR4 SDRAM modules use a registering clock driver device consisting of a register and a phase-lock loop (PLL). The device complies with the JEDEC DDR4 RCD specification.

To reduce the electrical load on the host memory controller's command, address, and control bus, Micron's RDIMMs utilize a DDR4 registering clock driver (RCD). The RCD presents a single load to the controller while redriving signals to the DDR4 SDRAM devices, which helps enable higher densities and increase signal integrity. The RCD also provides a low-jitter, low-skew PLL that redistributes a differential clock pair to multiple differential pairs of clock outputs.

Control Words

The RCD device(s) used on DDR4 RDIMMs, LRDIMMs, and NVDIMMs contain configuration registers known as control words, which the host uses to configure the RCD based on criteria determined by the module design. Control words can be set by the host controller through either the DRAM address and control bus or the I²C bus interface. The RCD I²C bus interface resides on the same I²C bus interface as the module temperature sensor and EEPROM.

Parity Operations

The RCD includes a parity-checking function that can be enabled or disabled in control word RC0E. The RCD receives a parity bit at the DPAR input from the memory controller and compares it with the data received on the qualified command and address inputs; it indicates on its open-drain ALERT_n pin whether a parity error has occurred. If parity checking is enabled, the RCD forwards commands to the SDRAM when no parity error has occurred. If the parity error function is disabled, the RCD forwards sampled commands to the SDRAM regardless of whether a parity error has occurred. Parity is also checked during control word WRITE operations unless parity checking is disabled.

Rank Addressing

The chip select pins (CS_n) on Micron's modules are used to select a specific rank of DRAM. The RDIMM is capable of selecting ranks in one of three different operating modes, dependant on setting DA[1:0] bits in the DIMM configuration control word located within the RCD. Direct DualCS mode is utilized for single- or dual-rank modules. For quad-rank modules, either direct or encoded QuadCS mode is used.

Data Buffer Operation and Description

Data buffers operate as 4-bit bidirectional data registers with differential strobes, designed for 1.2 V_{DD} operation. Each buffer has a dual 4-bit host bus interface connected to the memory controller and a dual 4-bit DRAM interface connected to two x4 DRAM devices. Each buffer has an input-only 4-bit control bus interface consisting of two dedicated control signals, a voltage reference input, and a differential clock signal.

All DQ inputs are pseudo-differentiated with an internal voltage reference. All DQ outputs are V_{DD}-terminated drivers that are optimized to drive single- or dual-terminated traces in DDR4 LRDIMM applications. The differential DQS strobes are used to sample the DQ inputs and are regenerated internally to drive the DQ outputs on the opposite side of the device.



64GB (x72, ECC, QR) 288-Pin DDR4 LRDIMM Data Buffer Operation and Description

Control inputs are sampled by the clock inputs, and each data buffer supports ZQ calibration for parity (with dedicated pins) and sequence error alerts.

Temperature Sensor with SPD EEPROM Operation

Thermal Sensor Operations

The integrated thermal sensor continuously monitors the temperature of the module PCB directly below the device and updates the temperature data register. Temperature data may be read from the bus host at any time, which provides the host real-time feedback of the module's temperature. Multiple programmable and read-only temperature registers can be used to create a custom temperature-sensing solution based on system requirements and JEDEC JC-42.2.

EVENT_n Pin

The temperature sensor also adds the EVENT_n pin (open-drain), which requires a pull-up to V_{DDSPD}. EVENT_n is a temperature sensor output used to flag critical events that can be set up in the sensor's configuration registers. EVENT_n is not used by the serial presence-detect (SPD) EEPROM.

EVENT_n has three defined modes of operation: interrupt, comparator, and TC_{CRIT}. In interrupt mode, the EVENT_n pin remains asserted until it is released by writing a 1 to the clear event bit in the status register. In comparator mode, the EVENT_n pin clears itself when the error condition is removed. Comparator mode is always used when the temperature is compared against the TC_{CRIT} limit. In TC_{CRIT} only mode, the EVENT_n pin is only asserted if the measured temperature exceeds the TC_{CRIT} limit; it then remains asserted until the temperature drops below the TC_{CRIT} limit minus the TC_{CRIT} hysteresis.

SPD EEPROM Operation

DDR4 SDRAM modules incorporate SPD. The SPD data is stored in a 512-byte, JEDEC JC-42.4-compliant EEPROM that is segregated into four 128-byte, write-protectable blocks. The SPD content is aligned with these blocks as shown in the table below.

Block	Range		Description
0	0–127	000h–07Fh	Configuration and DRAM parameters
1	128–255	080h–0FFh	Module parameters
2	256–319	100h–13Fh	Reserved (all bytes coded as 00h)
	320–383	140h–17Fh	Manufacturing information
3	384–511	180h–1FFh	End-user programmable

The first 384 bytes are programmed by Micron to comply with JEDEC standard JC-45, "Appendix X: Serial Presence Detect (SPD) for DDR4 SDRAM Modules." The remaining 128 bytes of storage are available for use by the customer.

The EEPROM resides on a two-wire I²C serial interface and is not integrated with the memory bus in any manner. It operates as a slave device in the I²C bus protocol, with all operations synchronized by the serial clock. Transfer rates of up to 1 MHz are achievable at 2.5V (NOM).

Micron implements reversible software write protection on DDR4 SDRAM-based modules. This prevents the lower 384 bytes (bytes 0 to 383) from being inadvertently programmed or corrupted. The upper 128 bytes remain available for customer use and are unprotected.

Electrical Specifications

Stresses greater than those listed may cause permanent damage to the module. This is a stress rating only, and functional operation of the module at these or any other conditions outside those indicated in each device's data sheet is not implied. Exposure to absolute maximum rating conditions for extended periods may adversely affect reliability.

Table 10: Absolute Maximum Ratings

Symbol	Parameter	Min	Max	Units	Notes
V_{DD}	V_{DD} supply voltage relative to V_{SS}	-0.4	1.5	V	1
V_{DDQ}	V_{DDQ} supply voltage relative to V_{SS}	-0.4	1.5	V	1
V_{PP}	Voltage on V_{PP} pin relative to V_{SS}	-0.4	3.0	V	2
V_{IN}, V_{OUT}	Voltage on any pin relative to V_{SS}	-0.4	1.5	V	

Table 11: Operating Conditions

Symbol	Parameter	Min	Nom	Max	Units	Notes
V_{DD}	V_{DD} supply voltage	1.14	1.20	1.26	V	1
V_{PP}	DRAM activating power supply	2.375	2.5	2.75	V	2
$V_{REFCA(DC)}$	Input reference voltage – command/address bus	$0.49 \times V_{DD}$	$0.5 \times V_{DD}$	$0.51 \times V_{DD}$	V	3
I_{VTT}	Termination reference current from V_{TT}	-750	-	750	mA	
V_{TT}	Termination reference voltage (DC) – command/address bus	$0.49 \times V_{DD} - 20\text{mV}$	$0.5 \times V_{DD}$	$0.51 \times V_{DD} + 20\text{mV}$	V	4
I_{IN}	Input leakage current; any input excluding ZQ; $0V < V_{IN} < 1.1V$	-2	-	2	μA	5
I_{ZQ}	Input leakage current; ZQ	-3	-	3	μA	6, 7
$I_{I/O}$	DQ leakage; $0V < V_{IN} < V_{DD}$	-4	-	4	μA	7
I_{OZpd}	Output leakage current; $V_{OUT} = V_{DD}$; DQ is disabled	-	-	5	μA	
I_{OZpu}	Output leakage current; $V_{OUT} = V_{SS}$; DQ and ODT are disabled; ODT is disabled with ODT input HIGH	-	-	50	μA	
I_{VREFCA}	V_{REFCA} leakage; $V_{REFCA} = V_{DD}/2$ (after DRAM is initialized)	-2	-	2	μA	7

- Notes:
- V_{DDQ} balls on DRAM are tied to V_{DD} .
 - V_{PP} must be greater than or equal to V_{DD} at all times.
 - V_{REFCA} must not be greater than $0.6 \times V_{DD}$. When V_{DD} is less than 500mV, V_{REF} may be less than or equal to 300mV.
 - V_{TT} termination voltages in excess of specification limit adversely affect command and address signals' voltage margins and reduce timing margins.
 - Command and address inputs are terminated to $V_{DD}/2$ in the registering clock driver. Input current is dependent on termination resistance set in the registering clock driver.
 - Tied to ground. Not connected to edge connector.
 - Multiply by number of DRAM die on module.

Table 12: Thermal Characteristics

Symbol	Parameter/Condition	Value	Units	Notes
T _C	Commercial operating case temperature	0 to 85	°C	1, 2, 3
T _C		>85 to 95	°C	1, 2, 3, 4
T _{OPER}	Normal operating temperature range	0 to 85	°C	5, 7
T _{OPER}	Extended temperature operating range (optional)	>85 to 95	°C	5, 7
T _{STG}	Non-operating storage temperature	-55 to 100	°C	6
RH _{STG}	Non-operating storage relative humidity (non-condensing)	5 to 95	%	
NA	Change rate of storage temperature	20	°C/hour	

- Notes:
1. Maximum operating case temperature; T_C is measured in the center of the package.
 2. A thermal solution must be designed to ensure the DRAM device does not exceed the maximum T_C during operation.
 3. Device functionality is not guaranteed if the DRAM device exceeds the maximum T_C during operation.
 4. If T_C exceeds 85°C, the DRAM must be refreshed externally at 2X refresh, which is a 3.9μs interval refresh rate.
 5. The refresh rate must double when 85°C < T_{OPER} ≤ 95°C.
 6. Storage temperature is defined as the temperature of the top/center of the DRAM and does not reflect the storage temperatures of shipping trays.
 7. For additional information, refer to technical note TN-00-08: "Thermal Applications" available at micron.com.

DRAM Operating Conditions

Recommended AC operating conditions are given in the DDR4 component data sheets. Component specifications are available at micron.com. Module speed grades correlate with component speed grades, as shown below.

Table 13: Module and Component Speed Grades

DDR4 components may exceed the listed module speed grades; module may not be available in all listed speed grades

Module Speed Grade	Component Speed Grade
-3G2	-062E
-2G9	-068
-2G6	-075
-2G3	-083
-2G1	-093E

Design Considerations

Simulations

Micron memory modules are designed to optimize signal integrity through carefully designed terminations, controlled board impedances, routing topologies, trace length matching, and decoupling. However, good signal integrity starts at the system level. Micron encourages designers to simulate the signal characteristics of the system's memory bus to ensure adequate signal integrity of the entire memory system.

Power

Operating voltages are specified at the edge connector of the module, not at the DRAM. Designers must account for any system voltage drops at anticipated power levels to ensure the required supply voltage is maintained.



I_{DD} Specifications

Table 14: DDR4 I_{DD} Specifications and Conditions – 64GB (Die Revision B)

Values are for the MT40A4G4 DDR4 TwinDie SDRAM only and are computed from values specified in the 16Gb (4 Gig x 4) component data sheet

Parameter	Symbol	2666	2400	Units
One bank ACTIVATE-PRECHARGE current	I _{CDD0}	2232	2178	mA
One bank ACTIVATE-PRECHARGE, wordline boost, I _{pp} current	I _{CPP0}	216	216	mA
One bank ACTIVATE-READ-PRECHARGE current	I _{CDD1}	2448	2394	mA
Precharge standby current	I _{CDD2N}	1980	1962	mA
Precharge standby ODT current	I _{CDD2NT}	2250	2250	mA
Precharge power-down current	I _{CDD2P}	1800	1800	mA
Precharge quiet standby current	I _{CDD2Q}	1890	1890	mA
Active standby current	I _{CDD3N}	2088	2034	mA
Active standby I _{pp} current	I _{CPP3N}	216	216	mA
Active power-down current	I _{CDD3P}	1962	1926	mA
Burst read current	I _{CDD4R}	3582	3384	mA
Burst write current	I _{CDD4W}	3420	3258	mA
Burst refresh current (1x REF)	I _{CDD5R}	2358	2304	mA
Burst refresh I _{pp} current (1x REF)	I _{CPP5R}	252	252	mA
Self refresh current: Normal temperature range (0°C to 85°C)	I _{CDD6N}	1980	1980	mA
Self refresh current: Extended temperature range (0°C to 95°C)	I _{CDD6E}	2160	2160	mA
Self refresh current: Reduced temperature range (0°C to 45°C)	I _{CDD6R}	1620	1620	mA
Auto self refresh current (25°C)	I _{CDD6A}	1209.6	1209.6	mA
Auto self refresh current (45°C)	I _{CDD6A}	1620	1620	mA
Auto self refresh current (75°C)	I _{CDD6A}	1980	1980	mA
Auto self refresh current I _{pp} current	I _{CPP6X}	288	288	mA
Bank interleave read current	I _{CDD7}	8100	7560	mA
Bank interleave read I _{pp} current	I _{CPP7}	486	468	mA
Maximum power-down current	I _{CDD8}	1800	1800	mA



Table 15: DDR4 I_{DD} Specifications and Conditions – 64GB (Die Revision D)

Values are for the MT40A4G4 DDR4 TwinDie SDRAM only and are computed from values specified in the 16Gb (4 Gig x 4) component data sheet

Parameter	Symbol	2933	2666	Units
One bank ACTIVATE-PRECHARGE current	I _{CDD0}	2286	2232	mA
One bank ACTIVATE-PRECHARGE, wordline boost, I _{pp} current	I _{CPP0}	216	216	mA
One bank ACTIVATE-READ-PRECHARGE current	I _{CDD1}	2502	2448	mA
Precharge standby current	I _{CDD2N}	1998	1980	mA
Precharge standby ODT current	I _{CDD2NT}	2340	2250	mA
Precharge power-down current	I _{CDD2P}	1800	1800	mA
Precharge quite standby current	I _{CDD2Q}	1890	1890	mA
Active standby current	I _{CDD3N}	2232	2178	mA
Active standby I _{pp} current	I _{CPP3N}	216	216	mA
Active power-down current	I _{CDD3P}	1998	1962	mA
Burst read current	I _{CDD4R}	3780	3582	mA
Burst write current	I _{CDD4W}	3744	3600	mA
Burst refresh current (1x REF)	I _{CDD5R}	2502	2448	mA
Burst refresh I _{pp} current (1x REF)	I _{CPP5R}	252	252	mA
Self refresh current: Normal temperature range (0°C to 85°C)	I _{CDD6N}	2016	2016	mA
Self refresh current: Extended temperature range (0°C to 95°C)	I _{CDD6E}	2196	2196	mA
Self refresh current: Reduced temperature range (0°C to 45°C)	I _{CDD6R}	1656	1656	mA
Auto self refresh current (25°C)	I _{CDD6A}	1209.6	1209.6	mA
Auto self refresh current (45°C)	I _{CDD6A}	1656	1656	mA
Auto self refresh current (75°C)	I _{CDD6A}	2016	2016	mA
Auto self refresh current I _{pp} current	I _{CPP6X}	288	288	mA
Bank interleave read current	I _{CDD7}	5274	5004	mA
Bank interleave read I _{pp} current	I _{CPP7}	504	486	mA
Maximum power-down current	I _{CDD8}	1800	1800	mA

Registering Clock Driver Specifications

Table 16: Registering Clock Driver Electrical Characteristics

DDR4 RCD01 devices or equivalent

Parameter	Symbol	Pins	Min	Nom	Max	Units
DC supply voltage	V_{DD}	–	1.14	1.2	1.26	V
DC reference voltage	V_{REF}	V_{REFCA}	$0.49 \times V_{DD}$	$0.5 \times V_{DD}$	$0.51 \times V_{DD}$	V
DC termination voltage	V_{TT}	–	$V_{REF} - 40mV$	V_{REF}	$V_{REF} + 40mV$	V
High-level input voltage	$V_{IH, CMOS}$	DRST_n	$0.65 \times V_{DD}$	–	V_{DD}	V
Low-level input voltage	$V_{IL, CMOS}$		0	–	$0.35 \times V_{DD}$	V
DRST_n pulse width	$t_{IN-IT_Power_stable}$	–	1.0	–	–	μs
AC high-level output voltage	$V_{OH(AC)}$	All outputs except ALERT_n	$V_{TT} + (0.15 \times V_{DD})$	–	–	V
AC low-level output voltage	$V_{OL(AC)}$		–	–	$V_{TT} + (0.15 \times V_{DD})$	V
AC differential output high measurement level (for output slew rate)	$V_{OHdiff(AC)}$	Yn_t - Yn_c, BCK_t - BCK_c	–	$0.3 \times V_{DD}$	–	mV
AC differential output low measurement level (for output slew rate)	$V_{OLDiff(AC)}$		–	$-0.3 \times V_{DD}$	–	mV

Note: 1. Timing and switching specifications for the register listed are critical for proper operation of DDR4 SDRAM RDIMMs. These are meant to be a subset of the parameters for the specific device used on the module. See the JEDEC RCD01 specification for complete operating electrical characteristics. Registering clock driver parametric values are specified for device default control word settings, unless otherwise stated. The RCOA control word setting does not affect parametric values.

Data Buffer Specifications

Table 17: Data Buffer Electrical Characteristics

DDR4 DB01 devices or equivalent

Parameter	Symbol	Pins	Min	Nom	Max	Unit
DC supply voltage	V_{DD}	–	1.14	1.2	1.26	V
DC reference voltage	BV_{REFCA}	BV_{REF}	$0.49 \times V_{DD}$	$0.5 \times V_{DD}$	$0.51 \times V_{DD}$	
Low-level input voltage	$V_{IL(static)}$	BCK_t, BCK_c (during clock stop)	0	–	$0.35 \times V_{DD}$	
Differential input cross point voltage range	$V_{IX(BCK)}$	BCK_t, BCK_c	–120	–	120	mV
Extended differential input cross point voltage range	$V_{IX_EX(BCK)}$		–150	–	150	
Average common mode DC voltage	$V_{CM(DC)}$	BCK_t, BCK_c	$0.46 \times V_{DD}$	$0.5 \times V_{DD}$	$0.54 \times V_{DD}$	V
Single-ended high level	V_{SEH}	BCK_t, BCK_c	DDR4-1866, 2133 $(V_{DD}/2) + 90$ DDR4-2400 $(V_{DD}/2) + 75$	–	–	mV
Single-ended low level	V_{SEL}	BCK_t, BCK_c	–	–	DDR4-1866, 2133 $(V_{DD}/2) - 90$ DDR4-2400 $(V_{DD}/2) - 75$	
AC input high	$V_{IH(AC)}$	BCK_t, BCK_c	DDR4-1866, 2133 $BV_{REFCA} + 90$ DDR4-2400 $BV_{REFCA} + 75$	–	–	mV
AC input low	$V_{IL(AC)}$	BCK_t, BCK_c	–	–	DDR4-1866, 2133 $BV_{REFCA} - 90$ DDR4-2400 $BV_{REFCA} - 75$	
Differential input high	$V_{IH,diff}$	BCK_t, BCK_c	DDR4-1866, 2133; 130 DDR4-2400; 100	–	–	mV
Differential input low	$V_{IL,diff}$	BCK_t, BCK_c	–	–	DDR4-1866, 2133; –130 DDR4-2400; –100	
AC differential input high	$V_{IH,diff(AC)}$	BCK_t, BCK_c	$2 \times (V_{IH(AC).MIN} - BV_{REFCA})$	–	–	mV
AC differential input low	$V_{IL,diff(AC)}$	BCK_t, BCK_c	–	–	$2 \times (V_{IL(AC).MAX} - BV_{REFCA})$	

Table 17: Data Buffer Electrical Characteristics (Continued)

DDR4 DB01 devices or equivalent

Parameter	Symbol	Pins	Min	Nom	Max	Unit	
AC output high	$V_{OH(AC)}$	All outputs except ALERT_n	–	$(0.7 + 0.15) \times V_{DD}$	–	V	
AC output low	$V_{OL(AC)}$		–	$(0.7 - 0.15) \times V_{DD}$	–		
DC output high	$V_{OH(DC)}$		–	$1.1 \times V_{DD}$	–	V	
DC output mid	$V_{OM(DC)}$		–	$0.8 \times V_{DD}$	–		
DC output low	$V_{OL(DC)}$		–	$0.5 \times V_{DD}$	–		
AC differential output high	$V_{OH,diff(AC)}$		–	–	$0.3 \times V_{DD}$	–	V
AC differential output low	$V_{OL,diff(AC)}$		–	–	$-0.3 \times V_{DD}$	–	
Junction temperature	T_j	–	0	–	125	C°	
Case temperature	T_{CASE}	–	–	–	TBD		
Input clamp current	I_{IK}	–	–	–	–50	mA	
output clamp current	I_{OK}	–	–	–	±50		
Continuous output current	I_O	–	–	–	±50		
Continuous output current each V_{DD} or V_{SS} pin	I_{CCC}	–	–	–	±100		

Note: 1. Data buffer parametric values are specified for the device default control word settings, unless otherwise stated.



Temperature Sensor with SPD EEPROM

The temperature sensor continuously monitors the module's temperature and can be read back at any time over the I²C bus shared with the serial presence-detect (SPD) EEPROM. Refer to JEDEC JC-42.4 EE1004 and TSE2004 device specifications for complete details.

SPD Data

For the latest SPD data, refer to Micron's SPD page: micron.com/SPD.

Table 18: Temperature Sensor with SPD EEPROM Operating Conditions

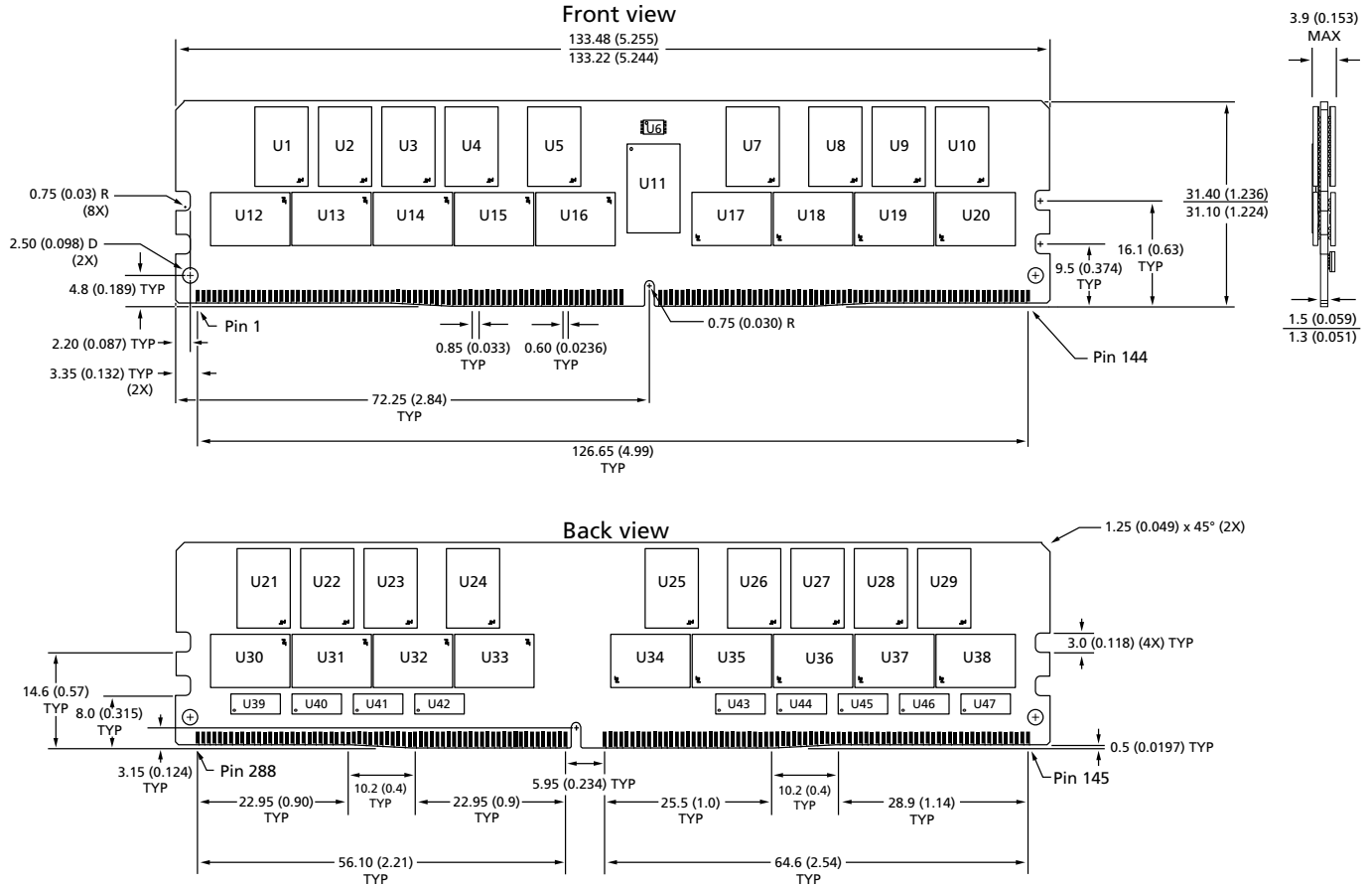
Parameter/Condition	Symbol	Min	Nom	Max	Units
Supply voltage	V _{DDSPD}	–	2.5	–	V
Input low voltage: logic 0; all inputs	V _{IL}	–0.5	–	V _{DDSPD} × 0.3	V
Input high voltage: logic 1; all inputs	V _{IH}	V _{DDSPD} × 0.7	–	V _{DDSPD} + 0.5	V
Output low voltage: 3mA sink current V _{DDSPD} > 2V	V _{OL}	–	–	0.4	V
Input leakage current: (SCL, SDA) V _{IN} = V _{DDSPD} or V _{SSSPD}	I _{LI}	–	–	±5	µA
Output leakage current: V _{OUT} = V _{DDSPD} or V _{SSSPD} , SDA in High-Z	I _{LO}	–	–	±5	µA

Table 19: Temperature Sensor and EEPROM Serial Interface Timing

Parameter/Condition	Symbol	Min	Max	Units
Clock frequency	f _{SCL}	10	1000	kHz
Clock pulse width HIGH time	t _{HIGH}	260	–	ns
Clock pulse width LOW time	t _{LOW}	500	–	ns
Detect clock LOW timeout	t _{TIMEOUT}	25	35	ms
SDA rise time	t _R	–	120	ns
SDA fall time	t _F	–	120	ns
Data-in setup time	t _{SU:DAT}	50	–	ns
Data-in hold time	t _{HD:DI}	0	–	ns
Data out hold time	t _{HD:DAT}	0	350	ns
Start condition setup time	t _{SU:STA}	260	–	ns
Start condition hold time	t _{HD:STA}	260	–	ns
Stop condition setup time	t _{SU:STO}	260	–	ns
Time the bus must be free before a new transition can start	t _{BUF}	500	–	ns
Write time	t _W	–	5	ms
Warm power cycle time off	t _{POFF}	1	–	ms
Time from power-on to first command	t _{INIT}	10	–	ms

Module Dimensions

Figure 3: 288-Pin DDR4 LRDIMM



- Notes: 1. All dimensions are in millimeters (inches); MAX/MIN or typical (TYP) where noted.
 2. The dimensional diagram is for reference only.

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This data sheet contains minimum and maximum limits specified over the power supply and temperature range set forth herein. Although considered final, these specifications are subject to change, as further product development and data characterization sometimes occur.