# Diamond is a material, not a system: no case for quantum memory in AI datacenters

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Abstract

An AI-written brief cast diamond as quantum memory between AI accelerators. The claim fails structurally: collectives copy data, superdense coding gives no net gain, and entanglement rates fall ~12.7 orders of magnitude short. Diamond's thermal conductivity holds up; its classical-electronics claims are overstated. Verification is partial and labeled as such.

Status: partial verification gate (2026-08-04). Two of eight research threads returned with sources before the session's search budget ran out; six stalled. This chapter reports what returned. The unrun threads are listed at the end as gaps, not negative results.

The chapter on exotic substrates for biology, *The Substrate Doesn't Save You*, asked whether quantum, analog or photonic hardware beats an honest digital baseline on biological workloads, and found that none does. This chapter puts the same question to a single material. The occasion was an enthusiastic brief, written by an AI system, arguing that diamond is the leading quantum-photonic material and that it belongs in AI datacenters as quantum memory between accelerators.

The gate found a pattern that is easy to state. The brief was right about diamond as a material and wrong about diamond in systems. Its claims got worse at each step from material property to device to system. The earlier chapter stands unchanged. This one adds a finer version of its lesson: a substrate can have excellent physics and still have no place in the architecture it is pitched for.

## The verdict table

| # | Claim in the brief | Verdict |
|---|---|---|
| 1 | Diamond quantum memory between AI accelerators eases datacenter communication bottlenecks | False |
| 2 | Quantum computers beat classical by many orders of magnitude on chemistry, drugs, materials, optimization and cryptography | Overstated: 1 of 5 survives |
| 3 | Diamond has the highest thermal conductivity of any bulk material | Sound |

| # | Claim in the brief | Verdict |
|---|---|---|
| 4 | Diamond works as a classical semiconductor, operating above 500 °C | Overstated |
| 5 | Ranking for solid-state quantum memory: diamond first, SiC second, rare-earth third | False precision |
| 6 | The SiC power-electronics ecosystem makes quantum SiC easier to scale | Partially sound |
| 7 | NV-centre quantum sensing is commercially mature | False as stated, not empty |

## The datacenter claim fails on structure, not on timing

The load-bearing claim fails on three independent grounds. None of them goes away with better engineering.

The traffic is the wrong kind. AI collectives such as all-reduce, all-gather and broadcast are copy operations. Quantum mechanics forbids copying or broadcasting unknown quantum states. The operations AI traffic is built from are the ones quantum links cannot structurally perform.

Superdense coding gives no net gain. Superdense coding sends two classical bits per transmitted qubit, but it uses up a pre-shared entangled pair, and distributing that pair took a photon through the same fibre. The net is one bit per channel use, the same as classical. It changes *when* photons cross, not how many.

The rate gap is about 12.7 orders of magnitude, and the most it could buy is 2×. The gate's estimate is that halving the 130 TB/s aggregate bandwidth of a current 72-GPU rack would need about 7.2 trillion entangled pairs per second. The best deployed-fibre entanglement swapping it found runs at 1.5 pairs per second over 17.6 km.

The gate looked for the strongest counter-argument and found a real one. Gragera Garcés and Pira's *Quantum ring all-reduce* (June 2026) is a genuine proposal for quantum communication in classical distributed learning, so "nobody proposes this" would have been false [3]. But its abstract caps the per-link communication saving at a *provably optimal factor of two*. Its real contribution is information-theoretically secure aggregation, which is a privacy result, not a bandwidth result [3]. Jaques and Rattew's survey of quantum RAM makes a related point: the control hardware that an active QRAM needs could often run a parallel classical algorithm just as fast instead [4].

Capacity and cooling close the question: about ten qubits per node against tens of gigabytes per stacked-memory package, and a cryostat per node against room-temperature co-packaged optics. Quantum memory for *distributed quantum computing*, where several quantum processors act as one, is a real research direction, but it carries no classical AI traffic.

### The quantum-advantage list: one of five survives

- Cryptography: sound. This is the one proven superpolynomial speedup. Gidney's 2025 estimate puts RSA-2048 at under a week on fewer than a million noisy qubits [5].
- Chemistry: the exponential claim is refuted. Lee et al., eighteen authors including Chan and Preskill, conclude that "it may be prudent to assume exponential speedups are not generically available" for ground-state chemistry [6].
- Optimization: collapsed. Babbush et al. show that quadratic, Grover-type speedups will not give advantage on early fault-tolerant machines [7].
- Drug discovery depends on chemistry and inherits its deflation. This matches the biology chapter's verdict.
- Quantum machine learning has been largely dequantized, per the gate; this chapter does not lean on it.

### Diamond as a classical semiconductor: overstated

The largest diamond logic circuit the gate could find is a NOR gate: two transistors and a load resistor. Demonstrated depletion- and enhancement-mode diamond circuits work up to about 200 °C, so ">500 °C" is an aspiration for logic, not a result. The gate also caught an inherited error. The most-cited high-temperature diamond transistor paper reports operation at 400 °C and 500 V [8], and the 500 is a voltage. Phosphorus donors, the n-type option, sit about 0.57 eV deep and are barely ionized at room temperature. The largest self-standing single-crystal substrate the gate found is 20 mm × 20 mm, which gives roughly 180 times less area than a 300 mm silicon wafer before purity or yield are counted.

### "The leading quantum memory" is false precision

No consensus ranking exists, and the winner depends on the metric:

| Metric | Leader |
|---|---|
| Memory time | Rare-earth ions: Eu:$Y_2SiO_5$ nuclear spins held coherence for six hours [9], about two orders of magnitude beyond diamond's best |
| Telecom-native emission | Erbium. The NV zero-phonon line is at 637 nm [16], so diamond must pay for lossy frequency conversion |
| Manufacturability | SiC and silicon |
| Demonstrated multi-node networks | Diamond: Delft's three-node NV network [11], and Harvard's two-node silicon-vacancy link over a 35 km deployed fibre loop in Boston [10] |

"Diamond" is also not one platform. NV and silicon-vacancy centres run at very different temperatures and make opposite trade-offs, so ranking them as one entry is itself a category error. The largest omission in the brief was silicon itself (T centres, G centres, erbium in silicon).

The head-to-head that did return favoured rare earths over SiC on networking, which is the reverse of the brief's ranking:

- Rare earths: two-node heralded entanglement of $^{171}$Yb ions at fidelity 0.723 ± 0.007 and 3.1 Hz [12], and erbium spin-photon entanglement over 15.6 km of fibre in the telecom band at 73(3)% fidelity and 1.48 Hz [13].
- SiC: the best is spin-photon entanglement at 75.7% fidelity with a $2 \times 10^{-4}$ generation probability per excitation [14]. There is no two-node entanglement yet.

SiC's real strength is coherence. Neutral divacancies reach single-spin $T_2$ above five seconds in isotopically purified material [15]. The gate notes a structural trade-off: the purification that buys this coherence removes the nuclear spins a multi-qubit register would need.

On claim 6, the gate found that the SiC ecosystem transfers the *photonics* half (wafer diameter, epitaxy, polishing, lithography, foundry processing). It does not transfer the *materials* half (isotopic purity, semi-insulating high-purity specifications, spectral stability), and that is where the quantum bottleneck is.

## NV sensing: real, but not in the way it is sold

Barry et al.'s review in *Reviews of Modern Physics* says it directly. State-of-the-art ensemble NV magnetometers reach pT/$\sqrt{\text{Hz}}$, while SQUIDs and SERF magnetometers reach fT/$\sqrt{\text{Hz}}$ and below. "This ∼1000× sensitivity discrepancy corresponds to a $\sim 10^6\times$ increase in required averaging time, which precludes many envisioned applications" [1]. The gate's comparison with incumbents found the same gap in every magnetometry band it checked. For biomagnetic sensing, the best NV figure it found was 9.4 pT/$\sqrt{\text{Hz}}$. Commercial optically pumped magnetometers are rated at a typical 7–10 fT/$\sqrt{\text{Hz}}$ and list at $7,700–$10,000 per sensor [20], so the NV penalty is about 1,100×. The gate found that the gap has not closed over the past decade. It also notes that one fielded NV device sits about 30× above its own shot-noise limit, and attributes the shortfall to laser noise, microwave instability and drift rather than to physics.

The field's own 2025 workshop report, with authors from MIT Lincoln Laboratory, Element Six and the University of Maryland, agrees. It says "commercial adoption remains limited," that "diamond technologies typically do not serve as drop-in replacements for existing technologies," and that "no facility is currently equipped to produce functionalized diamond at scale for quantum applications" [2].

What NV centres actually win on is not noise floor but room-temperature spatial resolution, dynamic range, absolute vector accuracy and environmental hardness. The one lane with commercial pull is semiconductor failure analysis: imaging currents through opaque packaging. The gate also caught its own error: a prominent quantum-sensing company had been counted toward NV maturity, but its sensors are atomic magnetometers, not diamond.

## What passed

Landing on a correct fact counts as a pass, not a non-event.

- Highest bulk thermal conductivity: sound. The qualifier "bulk" does real work, because it excludes graphene and carbon nanotubes. The gate's figures are about 2,000–2,400 W/mK for natural-abundance single crystal and about 3,300 W/mK for isotopically enriched $^{12}$C; the room-temperature record of 33.2 W/cm·K for a 99.93% $^{12}$C single crystal is summarised in Inyushkin et al. [22]. The closest challenger is cubic boron arsenide, now measured above 2,000 W/mK, which its authors describe as "on par with" single-crystal diamond rather than beating it [18].

- Heterogeneous integration is the right architecture. No single material does lasers, waveguides, modulation, memory, detection and nonlinearity well. The brief's structural intuition was correct and matches what the field does.

### What the project's own models already said

Two of the project's cost-model results bear on any photonic-substrate pitch, diamond included. In this project's model, the electronic interface accounts for 90.7% of the energy in a canonical batch-1 512×512 decode layer, at 9.77× the optical compute energy, identical for both substrate presets because the converters are substrate-independent silicon. The per-element gap is a 5 pJ converter against a 2 fJ multiply-accumulate, about 2,500×. Separately, forcing an optical-electrical-optical regeneration every 4 layers of an 80-layer model gave a 54.9× speedup against 55.4× without it, so solving all-optical nonlinearity buys less than 1% for decode.

One more check falls out of crystal symmetry. Diamond is centrosymmetric, so its second-order susceptibility vanishes unless the symmetry is broken [17]. It therefore has no Pockels effect, which is the basis of fast, low-loss electro-optic modulation. The brief listed electro-optic modulation among diamond's strengths and also rated it 4/5 for nonlinear optics; those claims are in tension.

### Cost: diamond is sold by the plate

Element Six's public e-shop lists thermal-grade polycrystalline plates from $160 for a $10 \times 10 \times 0.3$ mm TM100 to $490 for a $10 \times 10 \times 0.5$ mm TM220 [19]. In the gate's normalization, thermal grades cost about $10^3$ times as much per unit area as silicon, and optical-grade polycrystalline about $10^4$ times. The silicon reference is the project's own estimate, not a fetched price. Single-crystal, electronic-grade and quantum-grade material, the grades quantum work needs, had no public prices, and the workshop report says no facility yet produces functionalized diamond at scale [2].

### The thermal lane: promising, unresolved

Early evidence supports thermal management as diamond's strongest lane, with a caveat: interface engineering decides the outcome. In the papers the gate found, thin carbide interlayers cut thermal boundary resistance on GaN from 20.6 to 3.4–3.7 $m^2K/GW$, and 2.8 nm of extra interlayer cost a factor of four. Chemical-vapour-deposited films are not bulk diamond either: measured film conductivities of roughly 60–200 W/mK are 10–30× short of bulk. A GaN-on-diamond result showing a 5× drop in thermal resistance is a simulation, not a measurement. These thermal-lane papers were not re-verified for this chapter.

### What the evidence leaves standing

Diamond is not a computing substrate and not a datacenter component for AI traffic. On current evidence it is:

- a room-temperature nanoscale magnetic imaging material, with a real but narrow market in semiconductor metrology;
- the scientific leader in demonstrated multi-node quantum networking, with no near-term revenue;
- pending verification, a thermal material.

The one commercial signal the gate found in diamond's quantum lane fits this picture. It is a company building optical quantum interconnects on integrated diamond photonic circuits to link quantum processors into modular machines [21]. That is distributed quantum computing, not memory for AI accelerators.

## Gaps, not negative results

The following are unverified, not refuted:

1. Thermal lane (partial): packaging numbers for AI accelerators and stacked memory, cost per watt, shipping products, and the deciding question of whether 3C-SiC thin films beat diamond thin films in the regime that matters.
2. Cost (partial): single-crystal, electronic- and quantum-grade prices, reactor throughput, $^{12}C$ enrichment supply, polishing cost, and the cost trajectory compared with SiC.
3. Colour-centre comparison (partial): the comparison within diamond (NV, SiV, SnV, PbV), and silicon T centres.
4. Placement yield: the fraction of devices with exactly one centre, in the cavity, at the right wavelength.
5. Quantum-network commercial roadmaps and near-term revenue.
6. All-optical nonlinearity figures and photonic memory, including how diamond's third-order nonlinearity ranks against silicon, silicon nitride and chalcogenides.
7. The beyond-silicon materials table was not started. Its likeliest AI-relevant finding is GaN and SiC in datacenter power delivery, a real shipping market.

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## Provenance

Drawn from the research repository files `verification/diamond-photonics-gate.md` (gate report, 2026-08-04) and its companion `verification/exotic-substrates-for-biology.md`; the project's cost-model results come from `photonics/photonic/costmodel/interface.py` and `photonics/experiments/depth_cascadability_wall.py`; the thermal-lane arXiv sweep method is in `verification/frontier-computing-materials.md`.

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