PhaseGeometry Phase-Device Zoo: Towards a Unified Phase Description of Quantum and Semiclassical Devices

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December 2025

Abstract

In standard device physics, tunnelling, interference, negative differential resistance and charge quantisation are usually treated within a collection of separate models: Esaki diodes, resonant-tunnelling diodes, Gunn and IMPATT oscillators, Josephson junctions, SQUIDs, Aharonov–Bohm rings, quantum point contacts, single-electron transistors, quantum cascade lasers, and many variants. Within the PhaseGeometry programme it is natural to repackage these elements as members of a single "phase-device zoo", each realising a particular way in which a phase field controls transport. This short note provides a compact taxonomy of such devices and sketches a unifying phase description that can be linked both to the Z_2 phase medium and to the 5D phase-fibre picture.

1 Motivation

The PhaseGeometry framework is built around the idea that many apparently different physical systems can be understood as realisations of the same underlying phase structures. In the Z_2 programme the emphasis is on a binary phase medium and its rôle in cosmology and quantum foundations; in the 5D phase-fibre programme, phase is promoted to a genuine geometric coordinate ϕ attached to each spacetime point. In both cases, phase is not a mere auxiliary label but a dynamical object which can store, transport and process information.

From this point of view, a wide variety of condensed-matter and mesoscopic devices can be treated as *phase devices*: physical systems whose functionality is governed by the behaviour of some phase field (or an effective phase variable) and its coupling to currents, charges, and external fields. The purpose of this note is twofold:

- to collect a minimal "phase-device zoo"—a list of representative devices which already play, or can naturally play, a rôle in PhaseGeometry;
- to outline simple unifying principles which allow one to describe these systems within a single phase-based language, without replacing standard microscopic models.

2 Phase-device zoo

Instead of a wide table, we list representative devices as a structured taxonomy. For each entry we indicate (i) the physical regime, (ii) the dominant mechanism, (iii) the natural phase object, (iv) the presence or absence of negative differential resistance (NDR), and (v) the suggested rôle within the PhaseGeometry programme.

Esaki (tunnel) diode. *Regime:* semiconductor, heavily doped p–n junction with a very thin depletion region. *Mechanism:* direct tunnelling through the depletion barrier; overlap of filled and empty states on the two sides. *Phase object:* Bloch-wave phase across the junction; can be treated as an effective normal-state phase rotator with coupling $\alpha_N(d, V)$. *NDR:* yes (pronounced peak and valley in I–V). *PhaseGeometry rôle:* normal-state prototype of a phase rotator; simplest NDR device to rephrase in the PhaseGeometry language.

Resonant tunnelling diode (RTD). *Regime:* semiconductor heterostructure with a double barrier and a quantum well. *Mechanism:* resonant tunnelling via discrete levels in the well; current peaks when incoming energy matches a bound level. *Phase object:* phase of standing waves in the well; resonant phase condition across a multi-barrier stack. *NDR:* yes. *PhaseGeometry rôle:* clean example of a *resonant* phase rotator; normal-state analogue of Andreev / Josephson bound levels.

Gunn diode. *Regime:* bulk or heterostructure semiconductor with multi-valley conduction band. *Mechanism:* intervalley transfer and formation of travelling high-field domains in the bulk. *Phase object:* collective phase of a propagating space–charge / field domain. *NDR:* yes (effective NDR and microwave generation). *PhaseGeometry rôle:* example of NDR without tunnelling; macroscopic phase of a travelling pattern in the drift medium.

IMPATT / TRAPATT / BARITT diodes. *Regime:* semiconductor junctions and heterostructures operated at high fields and microwave frequencies. *Mechanism:* impact ionisation plus finite transit time; phase delay between RF field and current. *Phase object:* phase of the AC current relative to the RF field; a transit-time phase shift. *NDR:* yes at RF/microwave frequencies. *PhaseGeometry rôle:* high-frequency phase devices where negative resistance arises from controlled phase lags.

Josephson junction (SIS / SNS / Dayem bridge). *Regime:* superconductor–insulator–superconductor or superconductor–normal–superconductor weak link. *Mechanism:* Cooper-pair tunnelling and proximity effect in the weak region. *Phase object:* order-parameter phase difference $\Delta\phi$ across the weak link. *NDR:* no in DC I–V (but strongly nonlinear and hysteretic in some regimes). *PhaseGeometry rôle:* canonical superconducting phase rotator; base model for PhaseGeometry SNS/SIS devices and resonant field cells.

dc / rf SQUID. *Regime:* superconducting loop with one or two Josephson junctions. *Mechanism:* flux–phase conversion and interference of Josephson currents around the loop. *Phase object:* loop phase / enclosed flux; ϕ controlled by magnetic flux Φ through the loop. *NDR:* no (used primarily as a sensitive sensor). *PhaseGeometry rôle:* interferometric phase meter for the superconducting order parameter; bridge between local and global phase control.

Aharonov–Bohm ring. *Regime:* mesoscopic normal metal or 2DEG ring with coherent transport. *Mechanism:* quantum interference of two paths enclosing magnetic flux. *Phase object:* relative phase between paths; Aharonov–Bohm phase proportional to enclosed flux Φ. *NDR:* no (oscillatory conductance as a function of flux). *PhaseGeometry rôle:* minimal normal-state interferometer; pure example of phase-controlled conductance without superconductivity.

Quantum point contact (QPC). *Regime:* narrow constriction in a 2DEG or nanowire supporting a small number of 1D modes. *Mechanism:* mode quantisation and coherent transmission in 1D channels; conductance quantisation in steps of $2e^2/h$. *Phase object:* scattering phase of each transport mode; phase of transmission amplitudes. *NDR:* no (step-like conductance). *PhaseGeometry rôle:* prototype of phase-dependent, quantised conductance; natural entry point for PhaseGeometry in mesoscopic transport.

Single-electron transistor (SET). *Regime:* small normal or superconducting island connected by tunnel barriers. *Mechanism:* Coulomb blockade and charge quantisation; sequential tunnelling events. *Phase object:* phase of charge states on the island (dual to superconducting phase); an effective phase in the charge basis. *NDR:* not in simple DC I–V (Coulomb staircase rather than N-shaped characteristics). *PhaseGeometry rôle:* charge–phase dual to Josephson devices; connects PhaseGeometry to discrete charge transport and island devices.

Quantum cascade laser (QCL). *Regime:* semiconductor superlattice with multiple wells and barriers. *Mechanism:* cascaded resonant tunnelling and optical transitions along a ladder of engineered subbands. *Phase object:* phase of envelope states across the superlattice; phase matching between tunnelling and optical emission. *NDR:* no (functions as a gain medium). *PhaseGeometry rôle:* multistage phase-engineered tunnelling structure; example of extended phase engineering in the energy domain.

3 Unifying principles for phase devices

The list above deliberately mixes conventional semiconductor devices, superconducting elements and mesoscopic interferometers. The unifying idea is that each of them can be associated with an effective phase variable and a set of coupling coefficients which quantify how this phase responds to external drives and how it feeds back into observable currents and voltages.

3.1 Effective phase fields and phase rotators

The first step is to identify, for each microscopic setting, a natural phase object:

- in normal and semiconductor structures (Esaki, RTD, QPC, QCL), the phase of Bloch or envelope states provides a coarse-grained phase $\phi_{\mathrm{B}}(x)$ across the active region;
- in superconducting devices (Josephson junctions, SQUIDs), the order-parameter phase $\phi_{\mathrm{SC}}(x)$ is already explicit and directly controls supercurrents;
- in systems with travelling domains or delayed currents (Gunn, IMPATT), one can define a collective phase $\phi_{\mathrm{dom}}(x,t)$ of the propagating pattern;
- in charge-quantised systems (SET), a conjugate relation between discrete charge and a phase-like variable ϕ_Q naturally appears.

Once such a phase variable is identified, the device can be treated as a *phase rotator*: a local region in which the phase changes by some amount $\Delta\phi$ in response to external stimuli (bias voltage, magnetic flux, microwave drive, injected current). The microscopic details enter through effective coupling coefficients, schematically

$$\Delta\phi \;=\; \alpha(d, V, \omega, B, \ldots) \,\times\, (\mathrm{drive})\,, \tag{1}$$

with d the characteristic thickness or length of the active region and $(V, \omega, B, \ldots)$ denoting the applied voltage, frequency, magnetic field and other control parameters. In superconducting SNS/SIS links this is the $\alpha(d, \omega)$ already used in PhaseGeometry; for Esaki and RTD devices one can introduce a normal-state analogue $\alpha_N(d, V, \omega)$ calibrated to standard tunnelling models.

3.2 Negative differential resistance as phase restructuring

In devices with NDR (Esaki, RTD, Gunn, IMPATT), the same formal phase description can be used to reinterpret the origin of the non-monotonic current–voltage characteristic:

- in tunnelling devices (Esaki, RTD), the overlap of filled and empty states selects an effective set of phases which contribute to transport; as V is increased, the accessible phase channels reorganise, producing a peak and subsequent drop in current;
- in Gunn and IMPATT structures, the phase of domain motion or the phase lag between field and current crosses special values, leading to an effective negative resistance at certain frequencies.

In all these cases, NDR can be seen as a *restructuring of phase flow* through the device: a change in the pattern by which phase modes carry current, rather than a purely local change of resistance.

3.3 Interferometric phase meters

Aharonov–Bohm rings, SQUIDs and related interferometers play a special rôle as *phase meters.* They do not primarily act as phase rotators, but as devices that convert accumulated phase differences into measurable changes in conductance or critical current. In the PhaseGeometry picture, such elements link local phase dynamics to global constraints (e.g. flux quantisation in a loop) and provide natural interfaces between abstract phase fields and laboratory observables.

4 Directions for further development

The phase-device zoo suggests several concrete directions for the PhaseGeometry programme:

1. **Normal-state phase rotators.** Develop an explicit mapping between standard tunnelling models (Tsu–Esaki, NEGF) and effective normal-state phase rotators with coefficients $\alpha_N(d, V, \omega)$ for Esaki and resonant-tunnelling diodes.
2. **Unified SNS / Esaki / RTD language.** Formulate a common phase-based description in which superconducting SNS/SIS junctions and normal tunnelling devices appear as limiting cases of a single phase-rotator template, differing only by the type of phase field and microscopic calibration of α.
3. **Phase-engineered NDR.** Use the phase-flow viewpoint to design new NDR structures where the current peak and valley are controlled by engineered phase spectra (multi-barrier stacks, superlattices, hybrid SC/normal configurations).
4. **Charge–phase dual networks.** Extend the PhaseGeometry treatment to networks combining Josephson junctions, SETs and related devices, exploiting the duality between phase and charge to construct programmable phase media at the circuit level.
5. **Bridging to $\mathbf{Z}_2$ and 5D frameworks.** Interpret the effective device phases as coarse-grained manifestations of either (i) binary phase domains in the Z_2 medium, or (ii) trajectories in the 5D phase fibre (x^μ, ϕ). This provides a route to embed concrete mesoscopic devices into the broader cosmological and foundational context of PhaseGeometry.

5 Status and future work

The present note is intentionally conceptual and taxonomic. It collects standard devices into a common phase language but does not re-derive their transport properties from scratch within the Resonance formalism. In particular, normal-state tunnelling devices (Esaki, RTD) and mesoscopic interferometers (Aharonov–Bohm rings, QPCs) are treated at the level of their dominant mechanisms and natural phase variables, with microscopic details delegated to the standard condensed-matter literature.

Future work will include semi-technical mappings for selected devices, such as Esaki and resonant-tunnelling diodes and Aharonov–Bohm rings, where effective phase variables and normal-state coupling coefficients $\alpha_N(d, V, \omega)$ are derived directly from tunnelling and interference models. These worked examples will strengthen the link between the PhaseGeometry Resonance language and existing NEGF, Usadel and related approaches, and may be collected in a follow-up note.

6 Summary

This note does not attempt to replace any microscopic device model; rather, it collects a set of standard quantum and semiclassical devices and repackages them into a unified phase-based taxonomy. The key claim is modest but structural: once an effective phase field is identified, a wide variety of devices can be treated as phase rotators, phase meters, or phase-engineered media. This provides a common language linking superconducting SNS/SIS junctions, normal tunnelling devices, interferometers and charge-quantised elements, and prepares the ground for embedding concrete device physics into the Z_2 and 5D branches of the PhaseGeometry programme.