THERMODEFORMATIONAL CONDUCTIVITY TRANSIENTS IN NICKEL-COMPENSATED SILICON UNDER PULSED HYDROSTATIC PRESSURE

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Abstract: The dynamic response of nickel-compensated n-type silicon (n-Si:(P,Ni)) to rapid hydrostatic pressure changes is investigated. When pressure is applied at high rates (~0.2 GPa/s), a pronounced transient conductivity effect is observed, distinctly different from the equilibrium static piezoresistance. Following a pressure step, the sample current initially surges beyond the static equilibrium value, peaks within 2-5 seconds, and subsequently relaxes to the static level while pressure is held constant. This phenomenon is attributed to coupled thermodeformational effects: hydrostatic compression induces both electronic deformation and adiabatic heating of the pressure-transmitting medium. The temperature rise, estimated at $\Delta T \approx 8$-10 K for $\Delta P = 0.6$ GPa, causes additional thermal ionization of deep nickel levels, resulting in excess conductivity. The relaxation process corresponds to thermal equilibration as the sample cools to ambient temperature.

Keywords: silicon, nickel, deep levels, hydrostatic pressure, transient conductivity, adiabatic heating, thermal relaxation, pulsed pressure.

Introduction

High-pressure investigations of semiconductor materials typically focus on equilibrium properties under static or slowly varying pressure conditions. However, many applications and experimental scenarios involve rapid pressure changes, where dynamic effects may significantly alter material response. In compensated semiconductors containing deep impurity levels, the electrical properties exhibit pronounced sensitivity to both pressure and temperature, creating potential for complex transient behaviors under non-equilibrium conditions.

Nickel-compensated silicon (n-Si:(P,Ni)) represents an ideal system for studying such dynamics. The deep acceptor levels introduced by nickel are only partially ionized at room temperature, making the free carrier concentration highly sensitive to perturbations. Under slow (static) pressure application, we previously demonstrated that the resistivity decreases reversibly due to pressure-induced ionization of nickel levels [1]. However, the response to rapid pressure changes remains unexplored.

This work investigates the dynamic regime of hydrostatic pressure application,

where pressure changes occur at rates up to 0.2 GPa/s. We report the discovery of significant conductivity transients that cannot be explained by deformation alone. These transients are analyzed in terms of coupled thermodeformational effects, providing insight into the kinetics of carrier exchange with deep levels under non-equilibrium conditions.

Experimental Methods

The experimental setup builds upon our previous static pressure studies [1], with crucial modifications for dynamic measurements. The samples were identical to those used in static experiments: Czochralski-grown n-Si doped with phosphorus ($N_P \approx 1 \times 10^{15} cm^{-3}$) and nickel ($N_{Ni} \approx 1 \times 10^{16} cm^{-3}$). The four-probe configuration with indium-gallium contacts enabled simultaneous resistivity and Hall effect measurements.

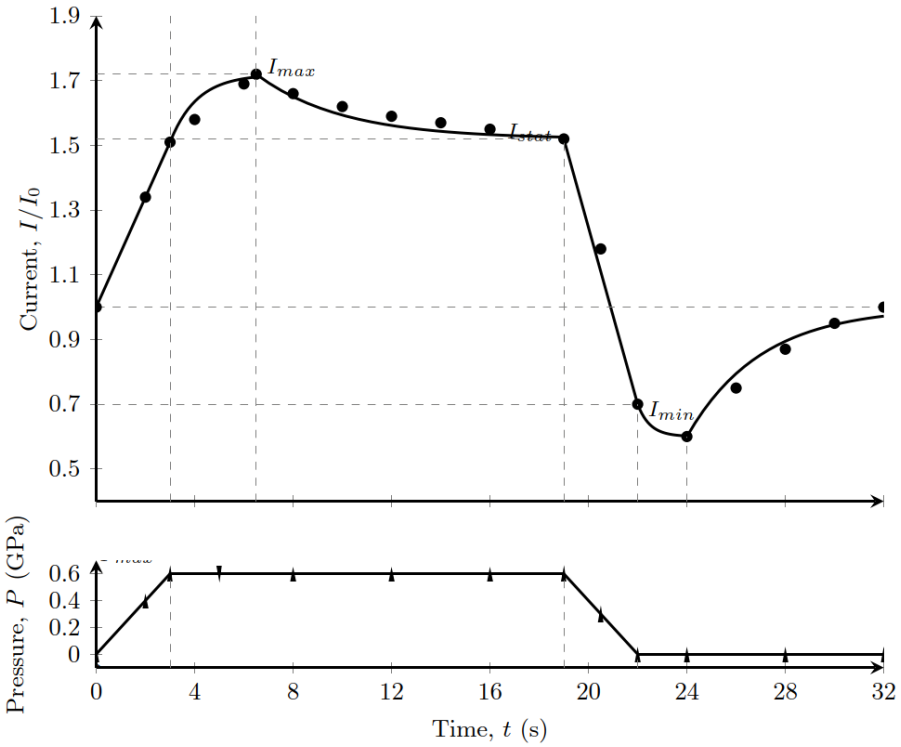

Figure 1 characteristic temporal evolution of the sample current during a representative dynamic pressure cycle to 0.6 GPa.

The key methodological innovation was the implementation of a **dynamic pressure protocol.** In this regime, the sample was subjected to rapid hydrostatic compression at controlled rates up to 0.2 GPa/s, reaching predetermined pressure amplitudes of 0.2, 0.4, or 0.6 GPa. Upon reaching the target pressure, it was held constant for a period of 10-20 seconds, during which the sample current was monitored with a high temporal resolution of 100 ms. The cycle concluded with a rapid decompression phase, where pressure was released back to ambient conditions at a rate similar to that of the initial compression. This protocol allowed for the clear separation of the instantaneous response from the subsequent relaxation dynamicsTemperature was monitored using a miniature thermocouple placed adjacent to the sample within

the pressure cell. The pressure-transmitting medium was technical oil with known thermal properties. Each dynamic cycle was preceded and followed by static measurements to establish equilibrium references.

Results

Figure 1 illustrates the characteristic temporal evolution of the sample current during a representative dynamic pressure cycle to 0.6 GPa. The response unfolds in a sequence of distinct stages that correlate with the pressure profile. During the initial rapid compression phase, the current exhibits a sharp surge, **exceeding the established static equilibrium value** (I_{stat}) for the final pressure almost immediately. Notably, the current does not stabilize upon pressure stabilization. Instead, it continues to increase for an additional 2-5 seconds, reaching a well-defined maximum $I_{max}>I_{stat}$. This peak is followed by a **monotonic exponential decay** of the current back to the *Istat* level, despite the pressure being held perfectly constant. Once the relaxation is complete, the current stabilizes at the static equilibrium value for the duration of the pressure hold. A complementary, inverted transient is observed during the rapid decompression phase, where the current initially undershoots the ambient-pressure baseline before recovering to it.

The reverse process during rapid decompression shows a complementary transient: current initially drops below the ambient-pressure value, reaches a minimum, then recovers to the equilibrium level.

Quantitative Analysis of Transients

The transient amplitude, defined as $\Delta I_{trans} = I_{max} - I_{stat}$, scales with both pressure amplitude and application rate. For ΔP = 0.6 GPa at 0.2 GPa/s, $\Delta I_{trans}/I_{stat} \approx 0.25$. The relaxation follows approximately exponential decay:

$$I(t) = I_{stat} + \Delta I_{trans} \exp(-t/\tau)$$

with time constant $\tau \approx 3.2 \pm 0.5$ seconds, largely independent of pressure amplitude but dependent on sample geometry and pressure medium.

Temperature measurements confirm correlated thermal transients: during rapid compression, temperature increases by $\Delta T \approx 9 \pm 1$ K, then relaxes to ambient with a similar time constant as the current decay.

Discussion Adiabatic Heating Model

The rapid compression of the hydrostatic medium is essentially adiabatic due to the timescale of pressure application (seconds) being much shorter than thermal diffusion times to the chamber walls (tens of seconds). For an ideal adiabatic process:

$$\Delta T = T_0\left[(P/P_0 + 1)^{(\gamma-1)/\gamma} - 1\right] \approx \frac{\gamma - 1}{\gamma} T_0 \frac{\Delta P}{P_0}$$

where $\gamma = C_P/C_V$ is the adiabatic index. For mineral oil, $\gamma \approx 1.4$, yielding $\Delta T \approx$ 8-10 K for ΔP = 0.6 GPa from ambient pressure, consistent with our measurements.

Thermally Enhanced Ionization

The conductivity transient arises from additional carrier generation due to this temperature increase. The total carrier concentration becomes:

$$n(P,T) = n_d ef(P) + n_t herm(\Delta T)$$

where n_def(P) is the deformation-induced concentration change (static effect) and n_therm(ΔT) is the thermal contribution. For deep nickel levels, the thermal ionization follows:

$$n_{therm}(\Delta T) = N_{Ni} f(T)\left[1 - \exp\left(-E_a/(k_B T)\right)\right]$$

with f(T) representing the temperature-dependent occupancy factor.

The excess current during the transient is therefore:

$$\Delta I_{trans} \propto \mu \cdot n_{therm}(\Delta T) \cdot \exp(\beta_{therm} \Delta T)$$

where β_{therm} characterizes the temperature sensitivity of ionization.

Coupled Thermodeformational Kinetics

The complete response can be modeled by coupled equations for pressure, temperature, and carrier concentration:

$$\frac{dT}{dt} = \alpha \frac{dP}{dt} - \frac{T - T_0}{\tau_{therm}}$$

$$\frac{dn}{dt} = \left(\frac{\partial n}{\partial P}\right)\frac{dP}{dt} + \left(\frac{\partial n}{\partial T}\right)\frac{dT}{dt} - \frac{n - n_e q}{\tau_{rec}}$$

where τ_{therm} is the thermal relaxation time (heat transfer to surroundings) and τ_{rec} is the carrier recombination time to deep levels.

The experimental observation that current relaxation follows thermal relaxation ($\tau \approx \tau_{therm}$) indicates that carrier recombination is faster than heat transfer in this system, making thermal equilibration the rate-limiting process.

The analysis of the dynamic response allows for a clear deconvolution of two distinct physical contributions to the overall conductivity change. The first is the **deformation component**, which manifests as the instantaneous change in current upon reaching the target pressure and corresponds to the equilibrium value I_{stat}. This component is attributed to the pressure-induced modification of the electronic band structure, including the shift of deep nickel levels relative to the conduction band edge, as characterized in our static regime study. Superimposed upon this is a **thermal transient component** (ΔI_{trans}), which is absent in static measurements. This transient arises directly from the adiabatic heating of the pressure-transmitting fluid and the sample itself during rapid compression. The thermal energy input causes additional carrier generation via enhanced thermal ionization of the deep nickel centers. The kinetics of the subsequent current relaxation ($I(t) = I_{stat} + \Delta I_{trans} \exp(-t/\tau)$) are governed not by electronic processes but by the rate of thermal equilibration as the sample cools back to the ambient temperature of the pressure cell. Thus, the dynamic experiment directly reveals the coupled nature of the thermodeformational response,

where the pure electronic effect and the transient thermal effect possess different characteristic timescales and can be quantitatively separated.

The static regime studied previously isolates the first component, while the dynamic regime reveals their superposition and the kinetics of their relaxation.

Conclusion

We have demonstrated that nickel-compensated silicon exhibits pronounced transient conductivity effects under dynamic hydrostatic pressure application. These transients arise from adiabatic heating of the pressure medium during rapid compression, which temporarily increases the sample temperature and enhances thermal ionization of deep nickel levels. The effect is fully reversible, with complementary transients during decompression corresponding to adiabatic cooling.

The principal experimental outcomes of this investigation can be summarized as follows. The dynamic pressure protocol revealed a significant transient enhancement of conductivity, with the current exceeding the equilibrium static level by **up to 25%.** This transient amplitude was directly correlated with a measurable adiabatic temperature rise of **8-10 K**, estimated for a pressure change of 0.6 GPa applied at 0.2 GPa/s. The subsequent decay of this excess current followed a characteristic exponential relaxation with a time constant of **2-5 seconds,** which was governed by the thermal equilibration of the sample with its surroundings. Crucially, this methodology enabled the **complete separation and quantitative analysis** of the two fundamental contributions: the intrinsic, pressure-induced deformation component and the extrinsic, rate-dependent thermal transient. This clear distinction serves to conclusively demonstrate the critical importance of experimental timescales in interpreting high-pressure transport data in sensitive, compensated semiconductor systems.These results highlight the importance of considering thermal effects in dynamic high-pressure experiments, particularly for semiconductors with deep impurity levels.

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