

Consistency checks for semiconductor contact extraction

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Finite-contact transmission-line model (TLM) fits can conceal geometry or de-embedding errors. We screen extraction of specific contact resistivity ρ_c and under-contact sheet resistance $R_{sh,uc}$ [1–3]. For positive de-embedded, width-normalized $Q(L) = R_c(L)W$, uniform linear-ohmic one-dimensional transport, equipotential metal, and shared positive parameters imply $1 < r < k$, with $r = Q(L)/Q(kL)$ and effective-length ratio $k > 1$.

A joint (r,k) uncertainty region permits conditional inversion if strictly interior; boundary overlap is inconclusive; disjointness from the closed domain indicates inconsistency under the model and error assumptions. Covariance reverses same-cutoff fixed-geometry ablations (Fig. 1a). All 1,500 Gaussian controls matched same-information constrained-feasibility decisions.

An omitted $+30 \Omega \cdot \mu m$ offset biased noiseless two-length fits by $+16.4\%$ in ρ_c and $+45.6\%$ in $R_{sh,uc}$ (Fig. 1b). All 30,000 noisy regions were interior, yet a nominal 95% third-length residual test rejected 6.90%. This blind spot warrants scrutiny of de-embedding. All results are synthetic; model compatibility does not establish physical validity.

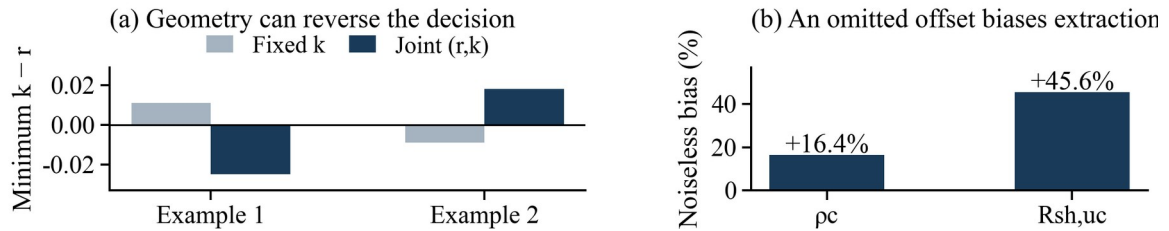


Figure 1. Synthetic same-cutoff covariance effects (a) and noiseless fitted bias from an omitted offset (b).

[1] G. K. Reeves and H. B. Harrison, IEEE Electron Device Lett. 3, 111–113 (1982).

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[2] C. Lan et al., Nanotechnology 19, 125703 (2008). doi:10.1088/0957-4484/19/12/125703.

[3] M. Ley et al., Mater. Sci. Forum 1192, 89–96 (2026). doi:10.4028/p-U2bkII.

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Supplement 1 Model and limits of conditional extraction

Model assumptions and observable

Let $Q_1 = R_{c,1}W_1$ and $Q_2 = R_{c,2}W_2$ denote positive width-normalized, de-embedded single-contact resistances at effective lengths L_1 and $L_2 = kL_1$. Assume uniform diffusive, linear-ohmic transport, one-dimensional current flow, an equipotential metal electrode (negligible distributed metal resistance), and shared positive ρ_c and $R_{sh,uc}$. The channel sheet resistance need not equal $R_{sh,uc}$. The measured two-terminal resistance must first be separated into its two contacts, channel, and other series terms.

$$Q(L) = A \coth(L/L_T), \quad A = \sqrt{(\rho_c R_{sh,uc})}, \quad L_T = \sqrt{(\rho_c / R_{sh,uc})}.$$

Strict bound and uniqueness

For $x = L_1/L_T > 0$ and $k > 1$, $r = Q_1/Q_2 = \tanh(kx)/\tanh(x)$. Since $\tanh$ is increasing, $r > 1$. Since $\tanh(y)/y$ decreases for $y > 0$, $r < k$. Both equalities are limiting cases only. Moreover $d \ln(r)/dx = 2k/\sinh(2kx) - 2/\sinh(2x) < 0$, because $\sinh(ky) > k \sinh(y)$. Thus r maps x in $(0, \infty)$ bijectively onto $(1, k)$, enabling a unique conditional inverse for any exact $k > 1$.

Exact threefold geometry and parameter recovery

Only for exact $k = 3$, write $t = \tanh(x)$. The identity $r = (3+t^2)/(1+3t^2)$ gives the closed-form inverse and sensitivity:

$$x = \operatorname{atanh} \sqrt{[(3-r)/(3r-1)]}, \quad dx/dr = -1/[(r-1)\sqrt{((3-r)(3r-1))}].$$

$$L_T = L_1/x, \quad A = Q_1 \tanh(x), \quad \rho_c = A L_T, \quad R_{sh,uc} = A/L_T.$$

For lengths in μm and Q in $\Omega \cdot \mu\text{m}$, L_T is in μm , ρ_c in $\Omega \cdot \mu\text{m}^2$, and $R_{sh,uc}$ in Ω/sq ; multiply ρ_c by 10^{-8} to obtain $\Omega \cdot \text{cm}^2$. As $x \rightarrow 0$, $Q \rightarrow \rho_c/L$ and $r \rightarrow k$. As $x \rightarrow \infty$, $Q \rightarrow A$ and $r \rightarrow 1$. Transfer-length conditioning deteriorates near both limiting ratios. Conditioning is parameter-specific: at fixed Q_1 and L_1 , $r \rightarrow k$ gives $L_T \rightarrow \infty$ and $R_{sh,uc} \rightarrow 0$, yet $\rho_c \rightarrow Q_1 L_1$. Thus poor transfer-length precision need not imply equally poor ρ_c precision.

Physical and inferential limits

De-embedding must separate each contact from channel and series terms. Propagate resistance, width, and effective-length covariance; never clip inadmissible data. Given an interior joint region, transform the region jointly; separate marginal extrema do not define a rectangular physical parameter region. The unconditional coverage of a region is not a post-selection guarantee after retaining only interior cases. Additional lengths test the combined transport, de-embedding, geometry, and error model. Their agreement cannot exclude mechanisms that mimic the same length dependence.

Contact shortening [2], contact-front/end extraction [3], finite metal resistance [4], and measurement–geometry uncertainty [5] are established. This gate is equivalent to constrained feasibility for the same ratio-space Gaussian region; it establishes no inferential superiority or experimental accuracy.

[4] M. Ahmad et al., Solid-State Electron. 46, 505–512 (2002). doi:10.1016/S0038-1101(01)00286-6.

[5] H.-J. Ueng, D. B. Janes, and K. J. Webb, IEEE Trans. Electron Devices 48, 758–766 (2001). doi:10.1109/16.915721.

Supplement 2 Decision-changing synthetic controls

Calibrating the joint region

Let $u = (Q_1, Q_2, L_1, L_2)$ and $z = (Q_1/Q_2, L_2/L_1)$. For small errors and stable positive denominators, use $\Sigma_z \approx J\Sigma_u J^T$; include width and de-embedding uncertainty in Q . For a Gaussian z estimate with known covariance, $(z-z_0)^T \Sigma_z^{-1} (z-z_0) \leq \chi^2_{2,0.95} = 5.991$ is a 95% joint region. Delta-method ratio regions are approximate. For n independent bivariate-normal replicates with sample mean z_{mean} and covariance S , use $n(z_{\text{mean}}-z)^T S^{-1} (z_{\text{mean}}-z) \leq 2(n-1)F_{2,n-2;0.95}/(n-2)$, $n > 2$; this calibration does not automatically apply to nonlinear raw-variable ratios.

Covariance can change the decision in either direction

For $(r,k) = (2.94, 3.00)$, standard deviations $(0.020, 0.040)$, and correlation 0.50, the nominal 95% joint ellipse is inconclusive although the same-cutoff fixed- k ablation is interior (example 1). With $(2.96, 3.00)$, $(0.020, 0.020)$, and correlation 0.90, the direction reverses. An ellipse is interior if $m - \sqrt{(c^T \Sigma_z a)} > 0$ for both margins $m = r-1$ and $k-r$, with $a = (1, 0)$ and $(-1, 1)$. Otherwise test disjointness by constrained Mahalanobis projection onto the closed wedge. At $c = 5.991$, the joint minimum $k-r$ is -0.02479 versus fixed- k $+0.01105$ for example 1, and $+0.01811$ versus -0.00895 for example 2 (reverse). The same multiplier isolates covariance, not equally calibrated one- and two-dimensional intervals.

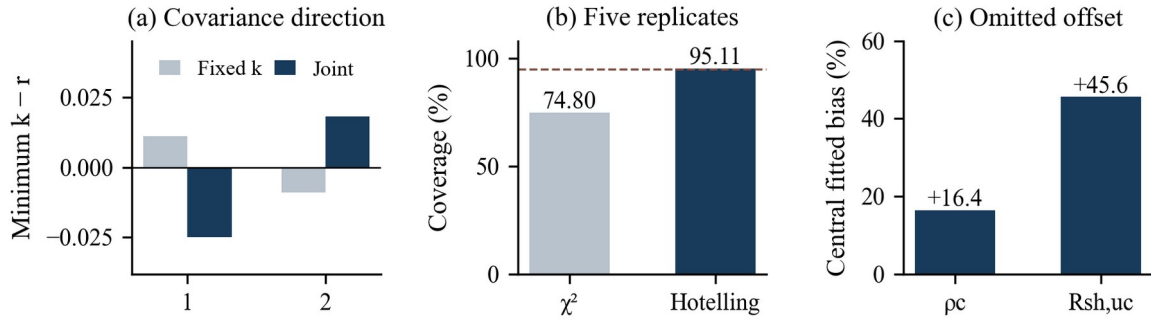


Figure S1. Synthetic controls for covariance direction (a), estimated-covariance coverage (b), and omitted-offset central fitted bias (c). No measured device data are shown.

In 1,500 seeded Gaussian cases, the analytic gate and a generic constrained-distance solver agreed: 174 interior, 701 overlap, 625 inconsistent. This checks equivalence, not improved inference. (b) At $n = 5$, χ^2 calibration covered 74,797/100,000 regions (74.80%); Hotelling calibration covered 95,105/100,000 (95.11%). A separate extreme raw-ratio case with denominator CV 50% covered 41,886/50,000 (83.77%); the delta approximation is unsuitable there.

(c) Ideal truth $\rho_c = 50 \Omega \cdot \mu\text{m}^2$, $R_{\text{sh,uc}} = 200 \Omega/\text{sq}$ and lengths $(0.5, 1.5, 1.0) \mu\text{m}$, with an omitted $+30 \Omega \cdot \mu\text{m}$ offset, yielded noiseless contaminated-input fits of 58.1937 and 291.2126 (+16.4% and +45.6%). With independent $\sigma_Q = 1 \Omega \cdot \mu\text{m}$ and 0.5% length noise, all 30,000 gates were interior; the held-out third-length central-delta 95% residual test rejected 2,069/30,000 cases (6.90%). These are central fitted biases, not Monte Carlo mean biases. This selected counterexample demonstrates a blind spot, not general power.