Characterization of High–Resolution TDI–CCD Imagers

Hon–Sum Philip Wong, Ying L. Yao,
and Francis P. Giordano

IBM Thomas J. Watson Research Center
Yorktown Heights, New York 10598, U.S.A.

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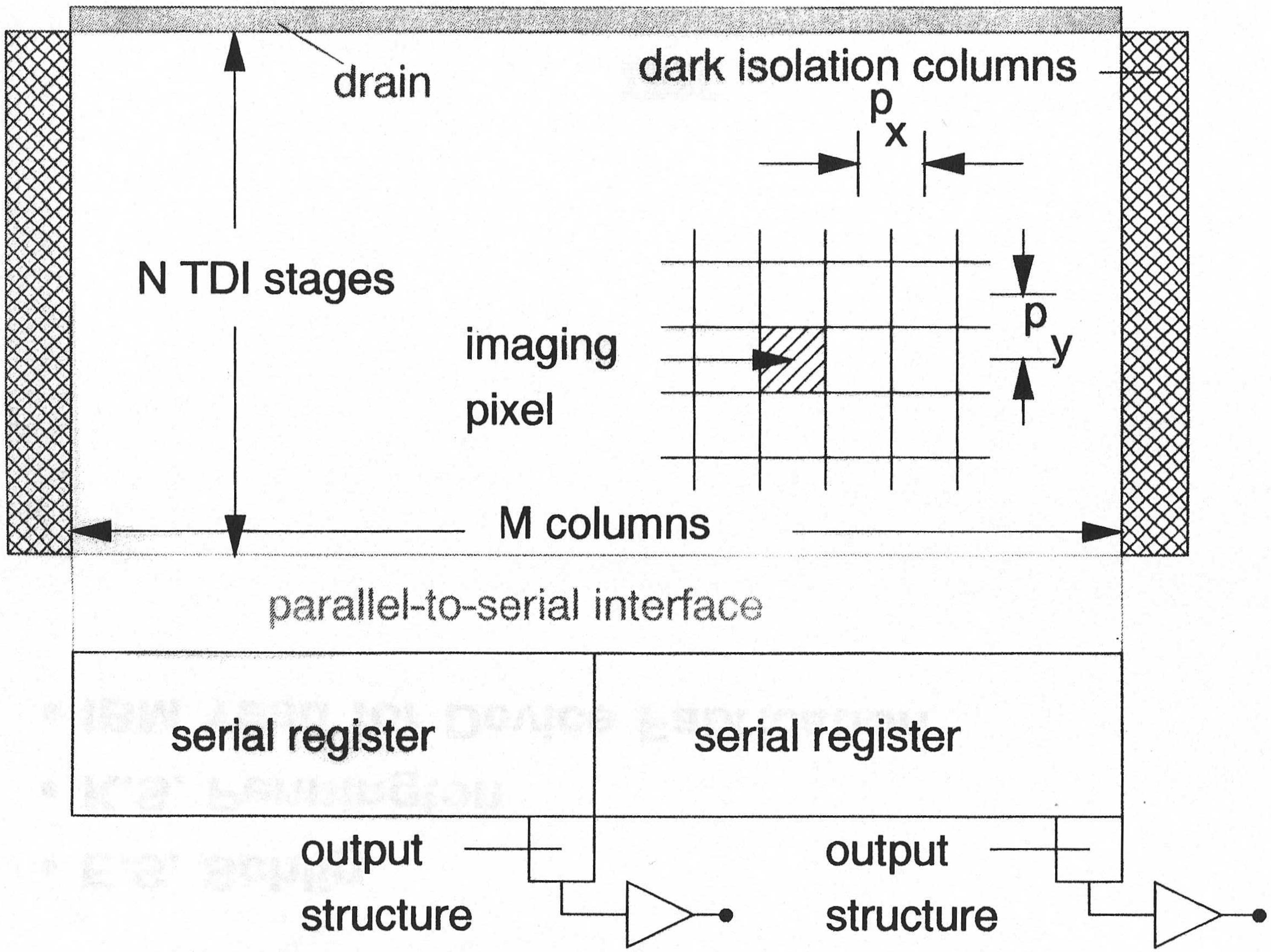


Time-Delay-and-Integration Charge Coupled Device (TDI CCD) Architecture

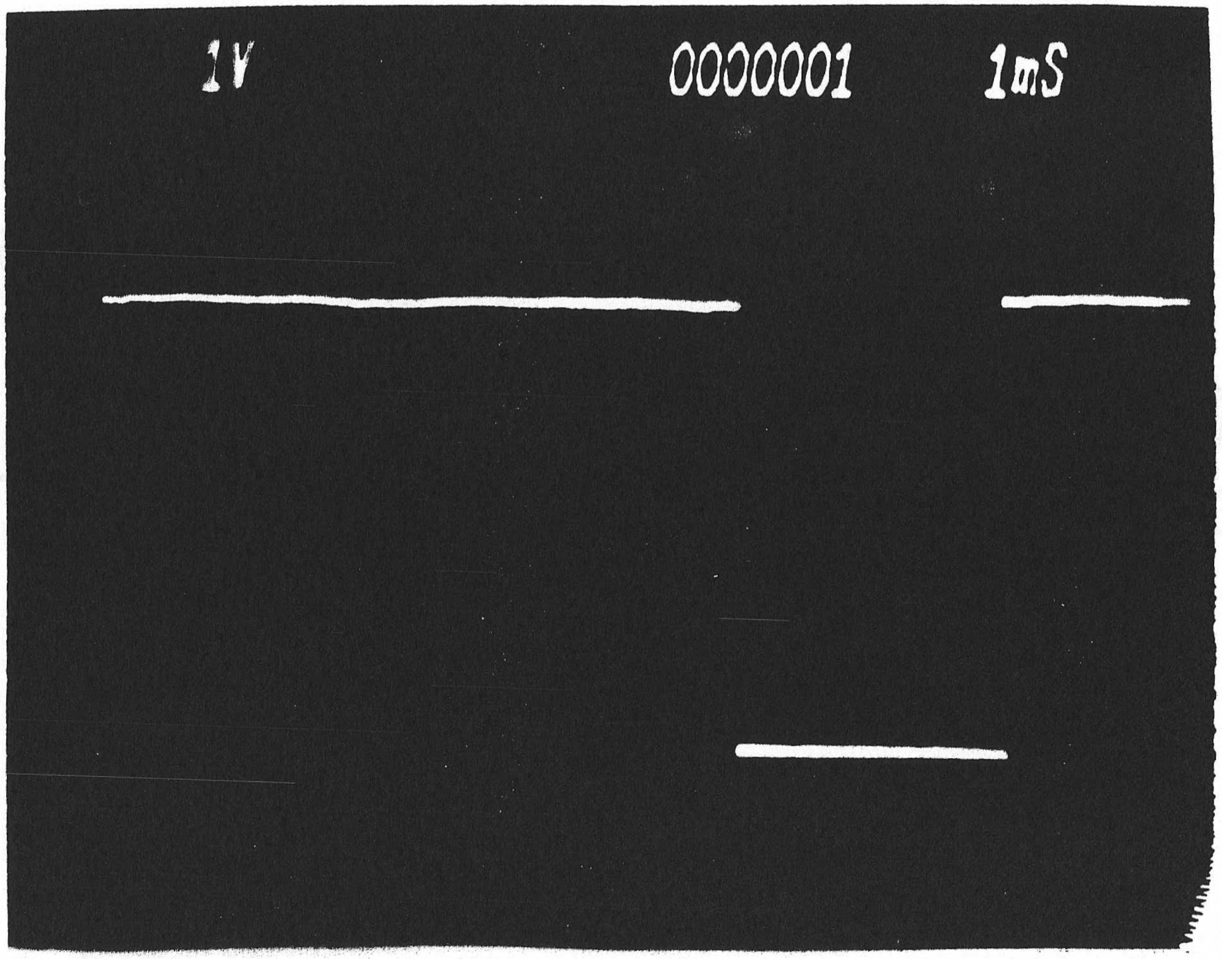


Fig. 1 Oscillograph illustrating the photoresponse uniformity of a 3072 × 32-stage TDI-CCD operated in TDI mode.

Mean-Variance Statistical Analysis

S = signal [ADU]

q = number of electrons detected [$\bar{e}$]

G = system gain [ADU/$\bar{e}$]

$$S = G \cdot q$$

$$\sigma_S^2 = \bar{G}^2 \cdot \sigma_q^2 + \bar{q} \cdot \sigma_G^2$$

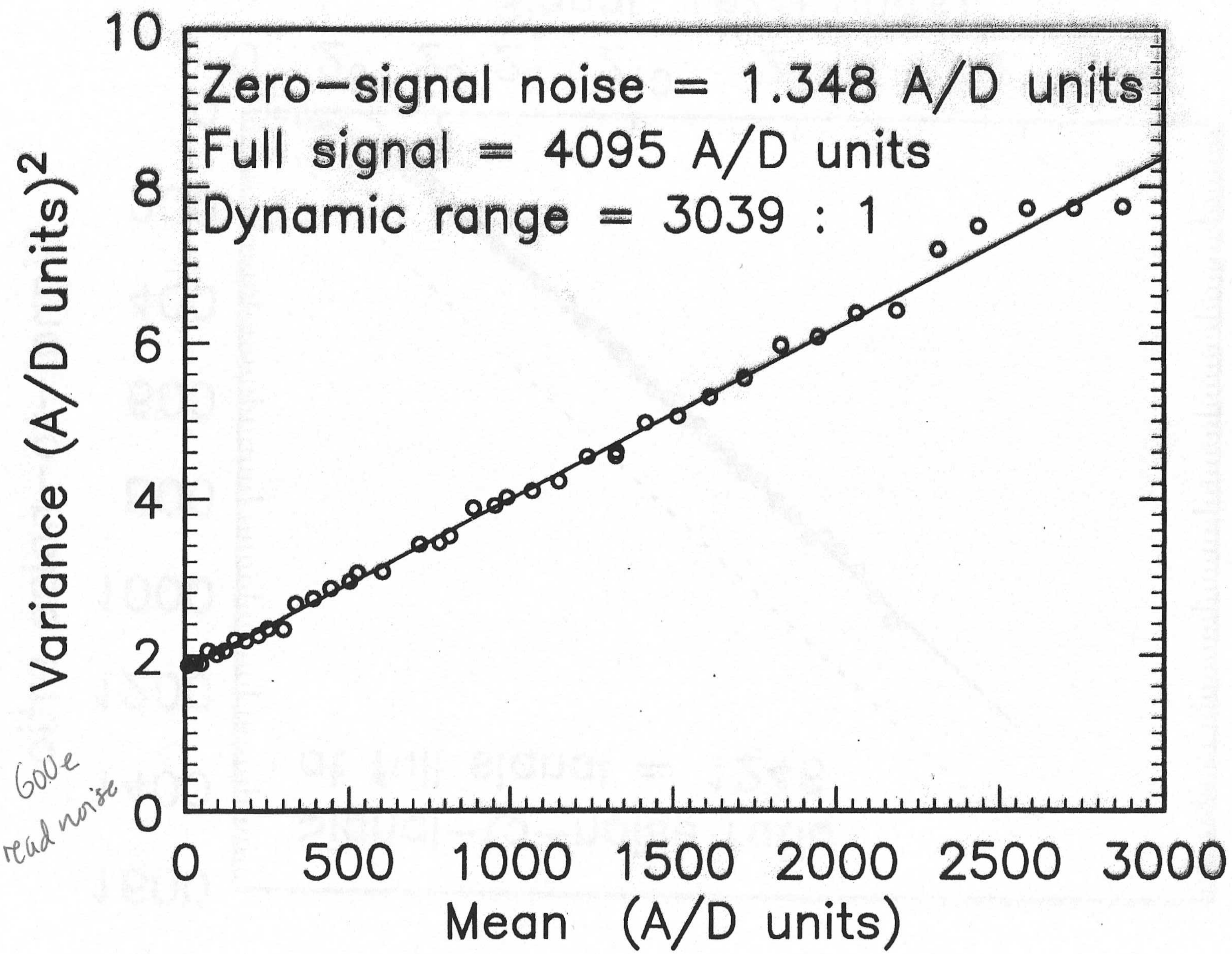
Photon shot noise limited regime: $\sigma_q^2 = \bar{q}$

$$\sigma_S^2 = \bar{G}^2 \cdot \bar{q} + \bar{q} \cdot \sigma_G^2 = \bar{S} \cdot \bar{G} \left[1 + \left(\frac{\sigma_G}{G}\right)^2 \right]$$

if $(\sigma_G / \bar{G}) << 1$

$$\boxed{\sigma_S^2 = \bar{S} \cdot \bar{G} + \sigma_{read}^2}$$

$$\bar{G}\,[\mathrm{ADU}/\bar{e}] = \underbrace{R\,[\mu V/\bar{e}]}_{\text{Responsivity}} \cdot \underbrace{A\,[\mathrm{ADU}/\mu V]}_{\text{A/D Conversion Gain}}$$



600e
read noise

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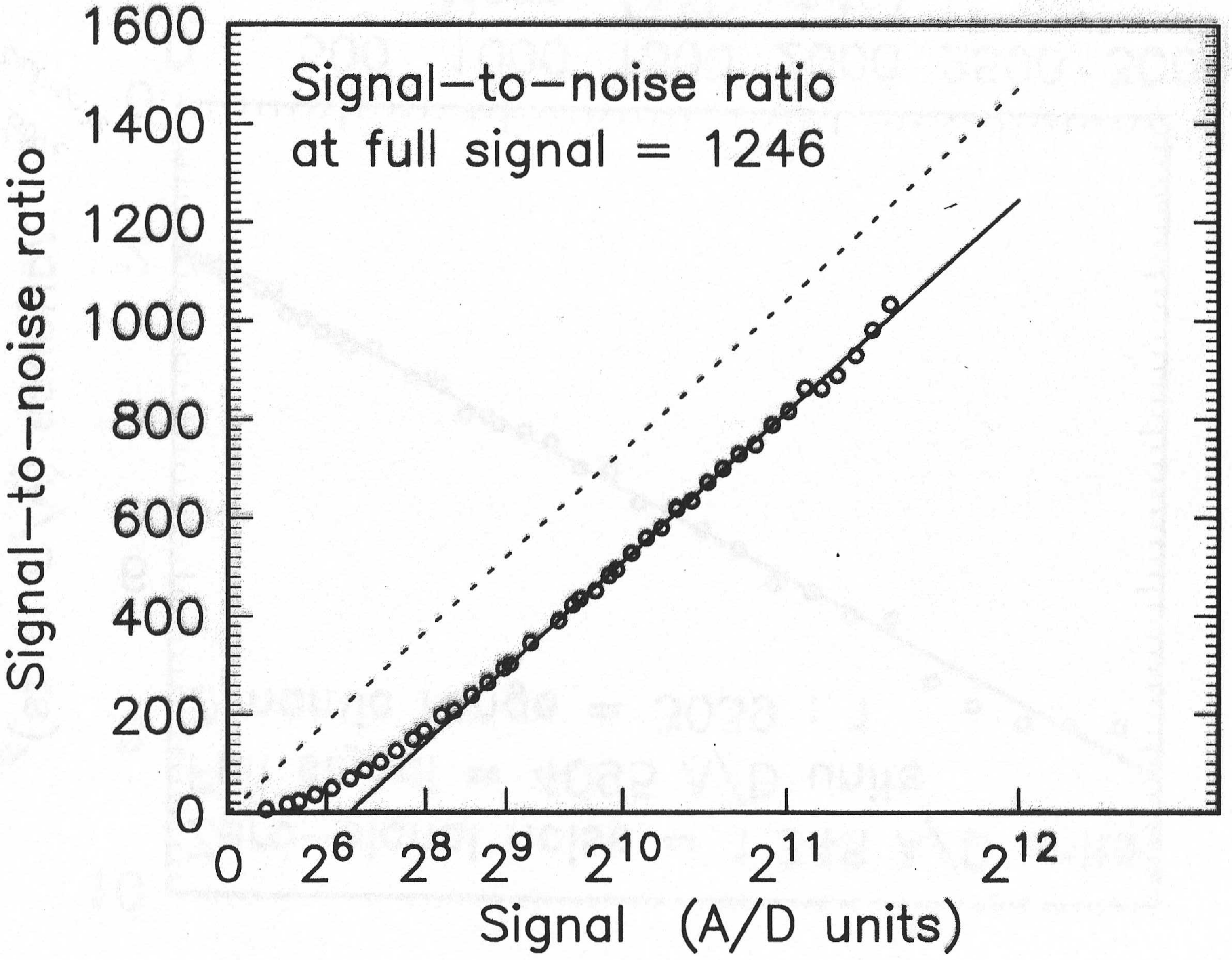

ps (6.01 7 May 1992):

ps PELSNR (GSIZE 6.0 8.0 ROTATE 90 FILL COLOR REPLACE BOTOPTION
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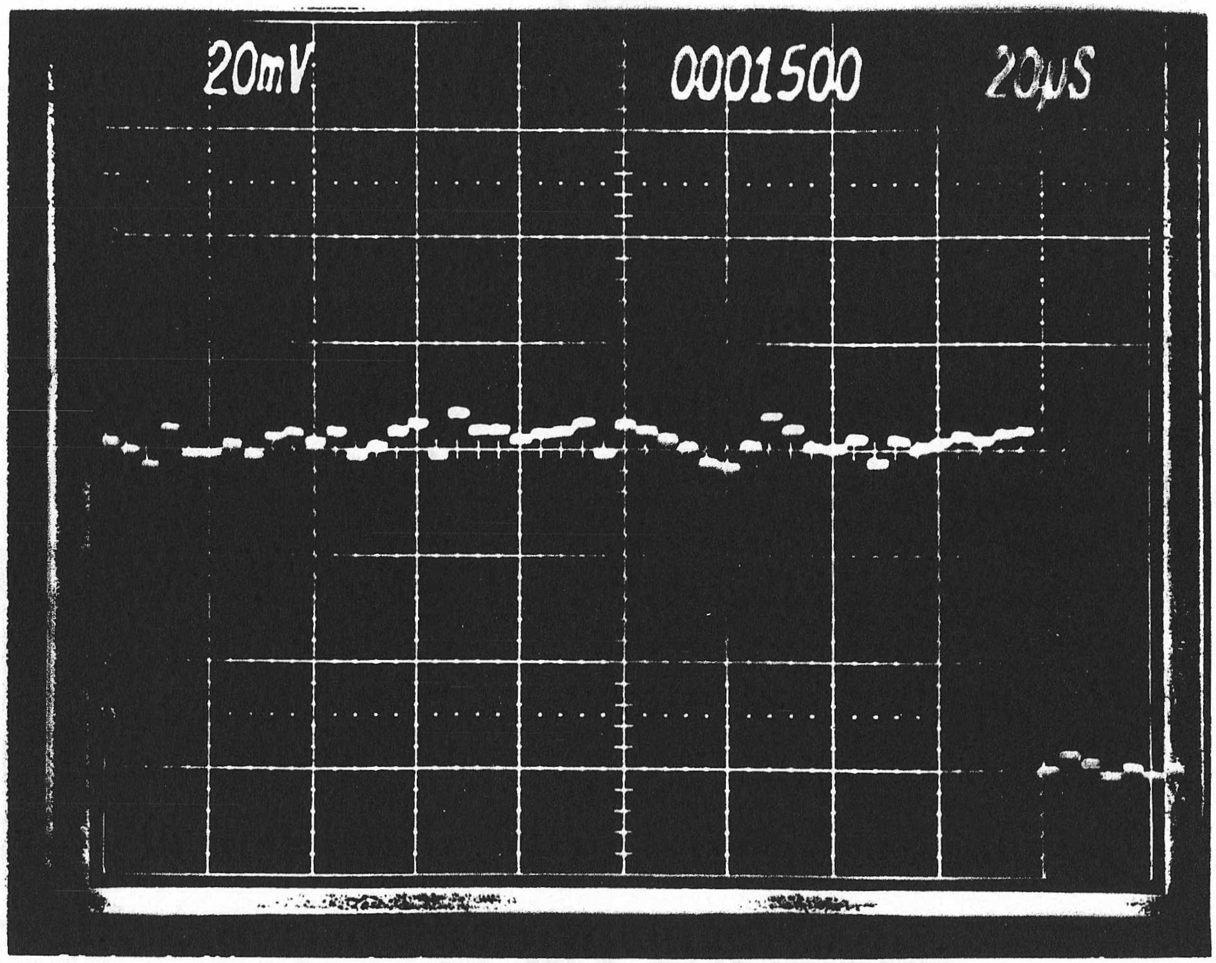


Fig. 2 Oscillograph illustrating the dark current uniformity of a 3072 × 32-stage TDI-CCD operated in TDI mode.

Hot–carrier–induced photon emission

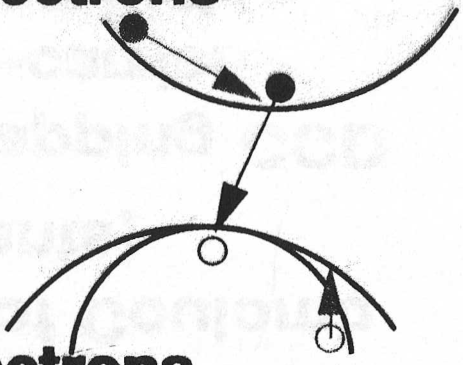
- Device performance: photons generate minority carriers in the substrate
  - DRAM holding time [Chatterjee, IEDM 1979, p.14]
  - Dark current in CCD's [Matsunaga, APL 1978, p.335]
  - Base current in bipolars [Ishiuchi, IEDM 89, p.803]
- Understanding device physics:
  - photon energy spectrum can be a probe of the channel hot–electron energy distribution [Toriumi, T–ED 87, Lanzoni, IEDM 90]
  - need a physical model to infer channel hot–electron distribution from photon energy spectrum

Objectives of the experiments

- Study photon emission mechanism for $h\nu \geq E_g$
  - device performance
  - channel hot–electron energy distribution
  - monitor photon intensity by measuring minority current collected by remote doide
- Verify the Bremsstrahlung and electron–hole recombination mechanisms
  - Bremsstrahlung $\propto$ number of Coulomb centers (ionized drain dopants)
- Use n–MOSFET's with an overlapping CCD gate structure to move the hot–carrier population away from the drain junction

Photon emission mechanisms

- Bremsstrahlung of channel hot-electrons with ionized drain dopants
  - intraband transition
  - photon energy continuum
- Recombination of channel hot-electrons with holes from impact ionization
  - interband transition
  - photon energy cut off below bandgap
- Radiative transition of holes between light-hole band and heavy-hole band
  - photon energy below bandgap



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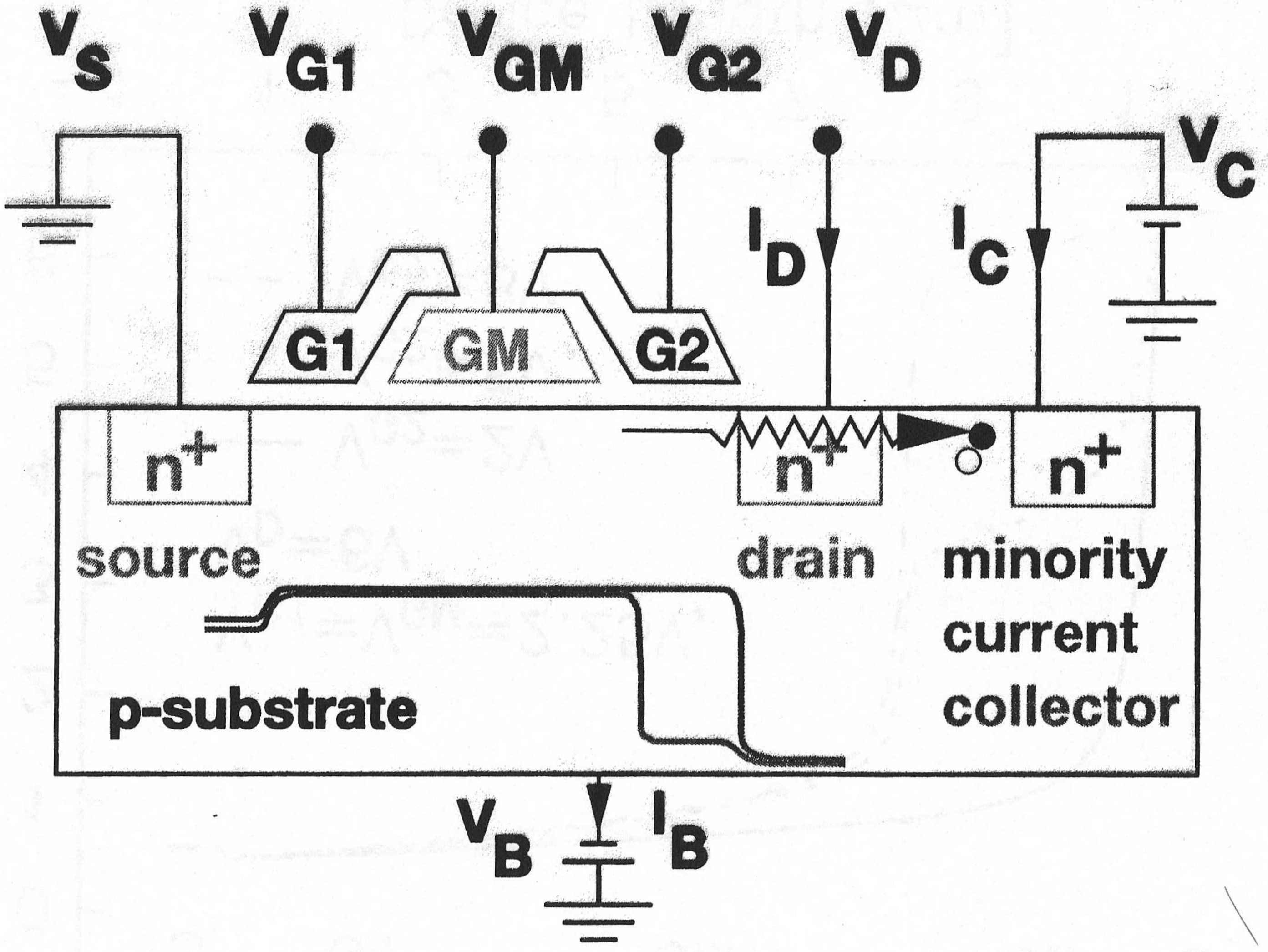
V_S
V_{G1}
V_{GM}
V_{G2}
V_D
V_C
I_D
I_C
G1
GM
G2
n^+
n^+
n^+
source
drain
minority
current
collector
p-substrate
V_B
I_B

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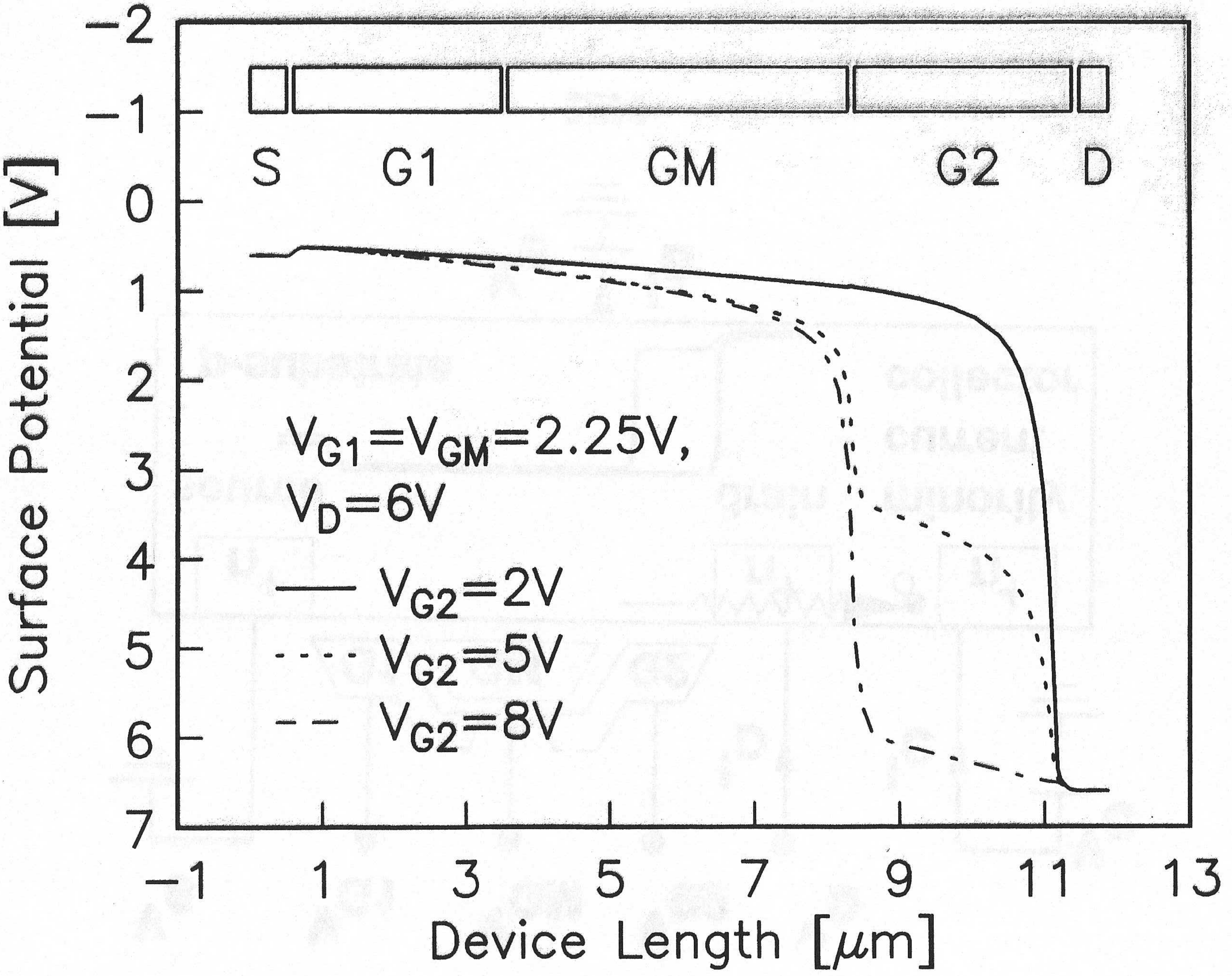
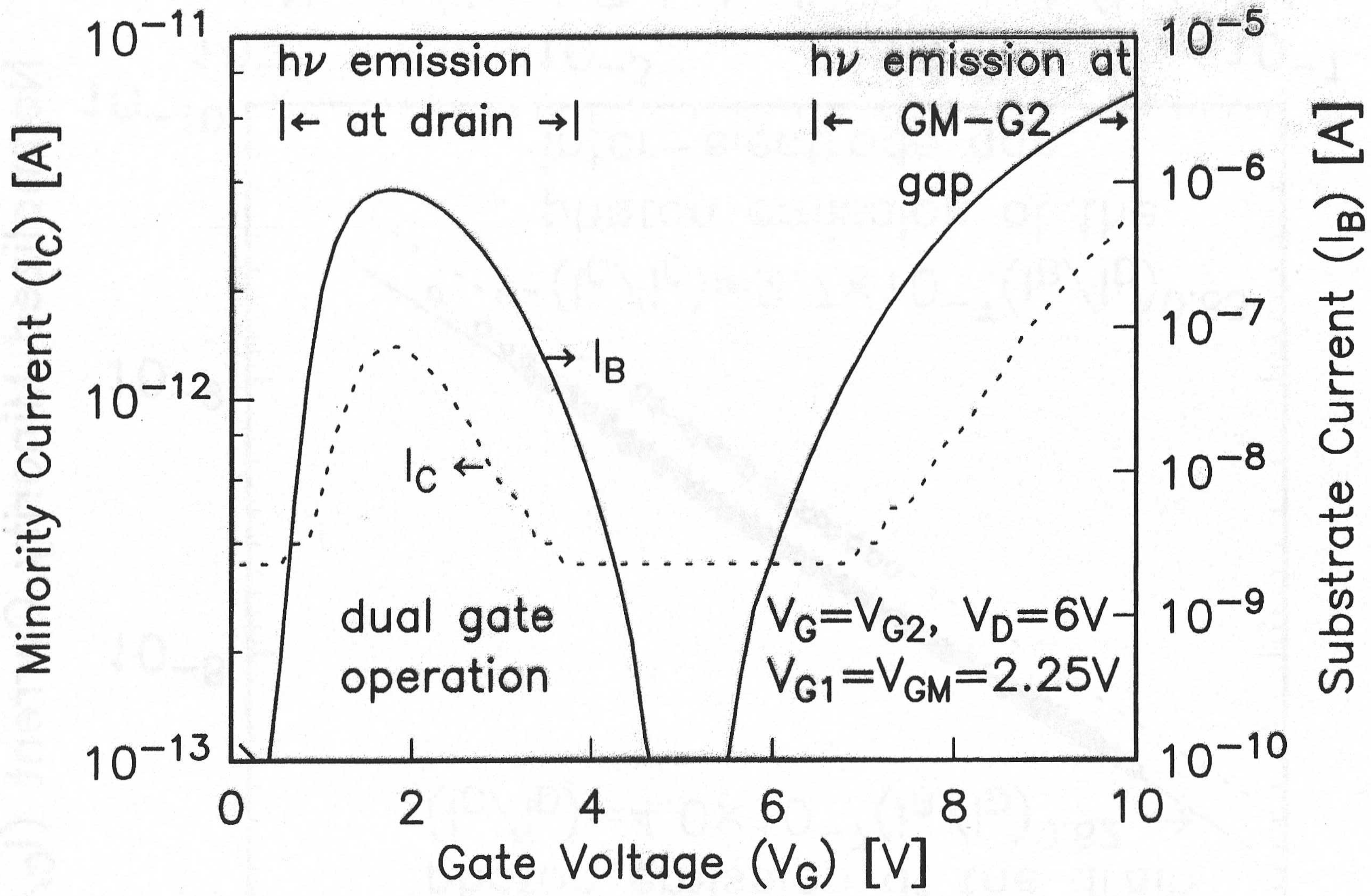
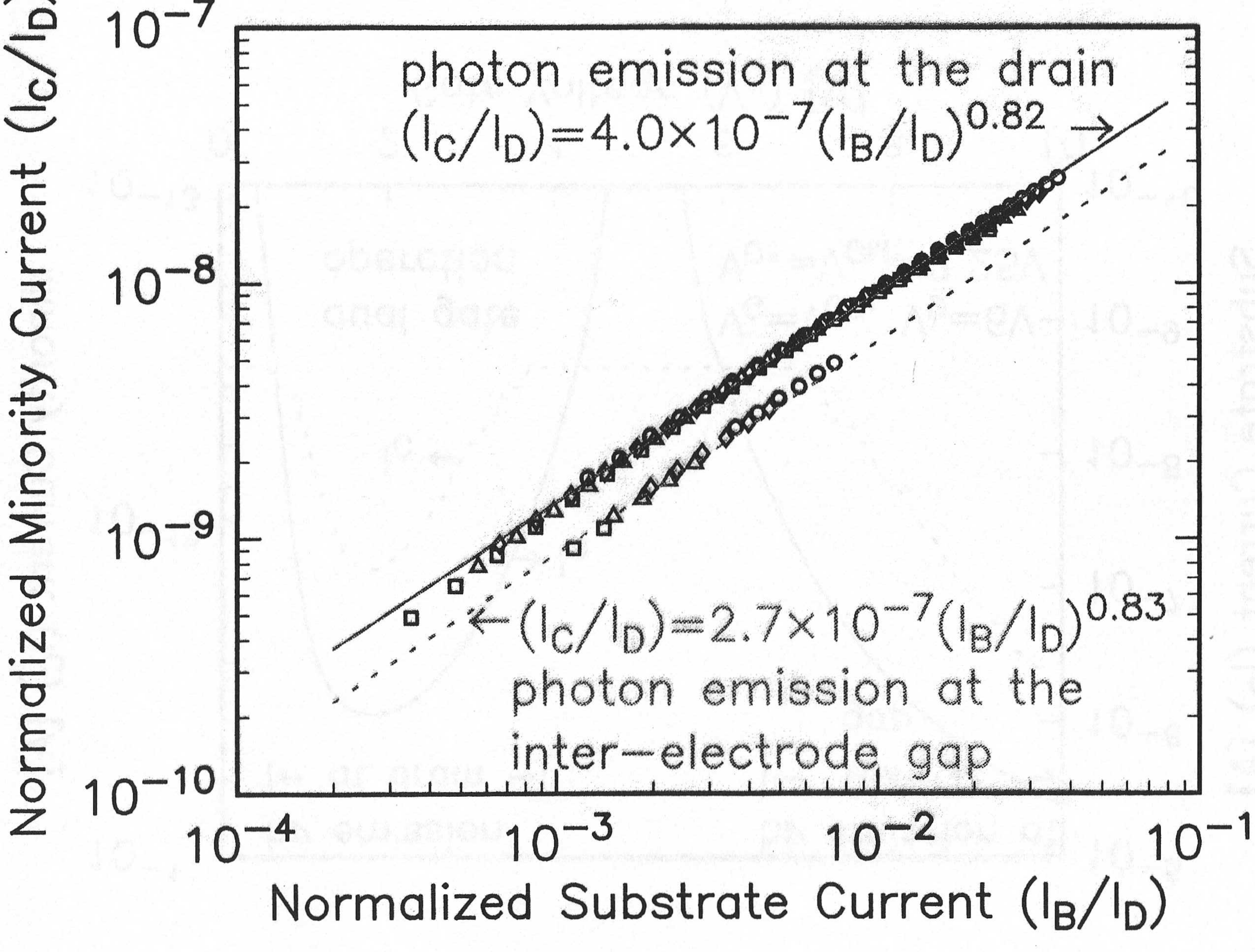

S
G1
GM
G2
D
$V_{G1}=V_{GM}=2.25V$,
$V_D=6V$
$V_{G2}=2V$
$V_{G2}=5V$
$V_{G2}=8V$
Surface Potential [V]
−2
−1
0
1
2
3
4
5
6
7
−1
1
3
5
7
9
11
13
Device Length [μm]


10−11
10−12
10−13
Minority Current (I_C) [A]
10−5
10−6
10−7
10−8
10−9
10−10
Substrate Current (I_B) [A]
0
2
4
6
8
10
Gate Voltage (V_G) [V]
hν emission
|← at drain →|
hν emission at
|← GM−G2 →
gap
→ I_B
I_C ←
dual gate
operation
V_G=V_G2, V_D=6V
V_G1=V_GM=2.25V


photon emission at the drain
$(I_C/I_D)=4.0\times10^{-7}(I_B/I_D)^{0.82}$ →
← $(I_C/I_D)=2.7\times10^{-7}(I_B/I_D)^{0.83}$
photon emission at the inter−electrode gap
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Normalized Minority Current (I_C/I_D)
Normalized Substrate Current (I_B/I_D)

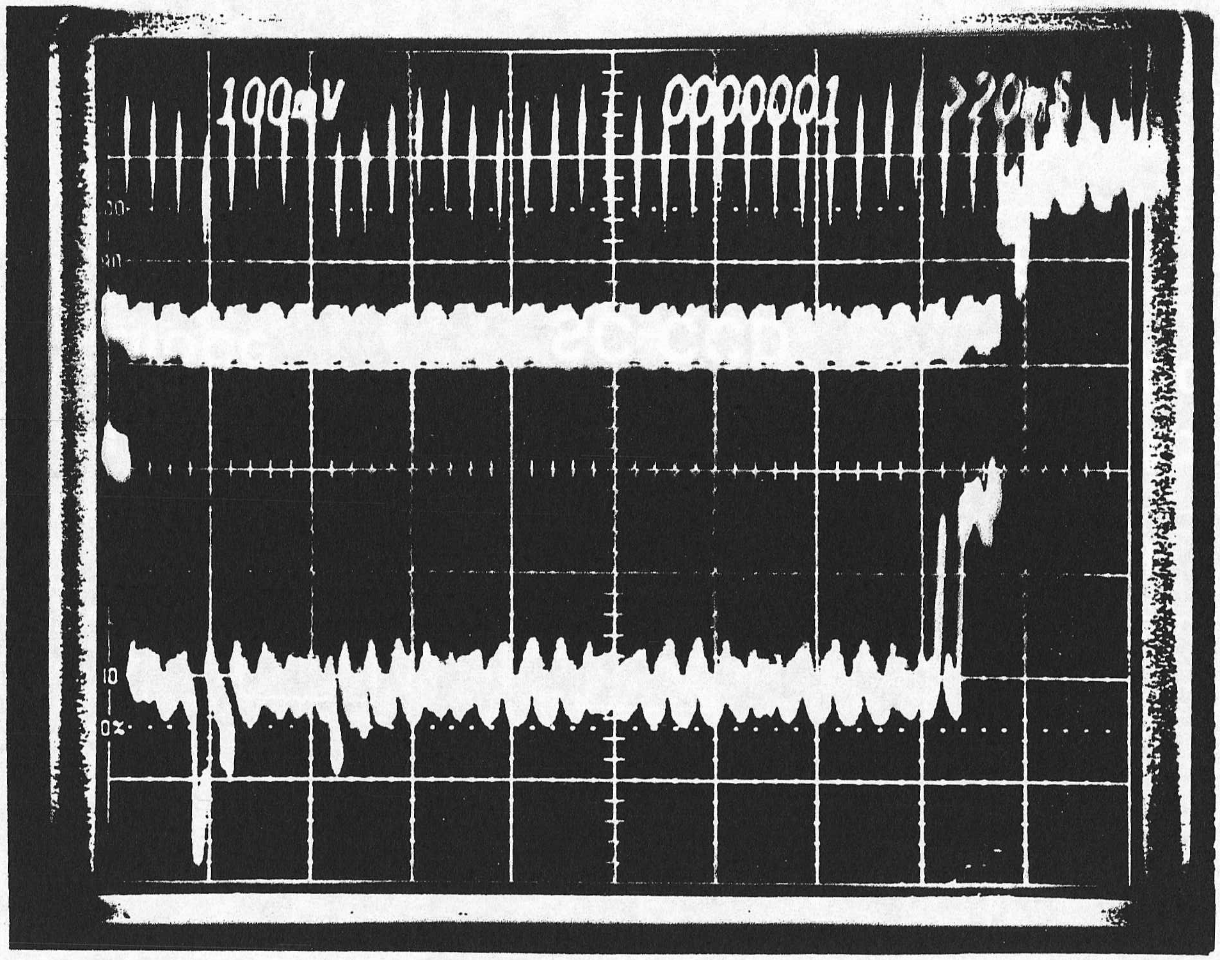
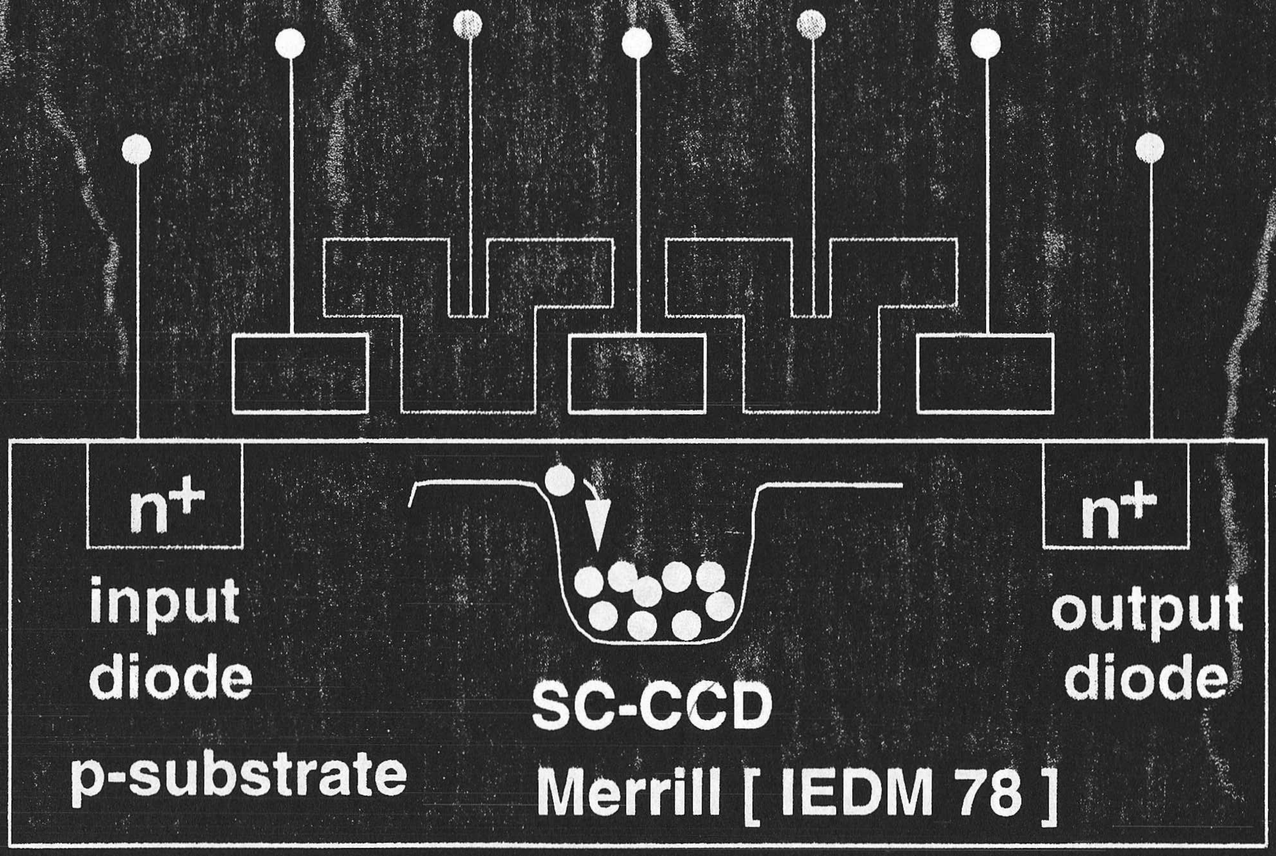


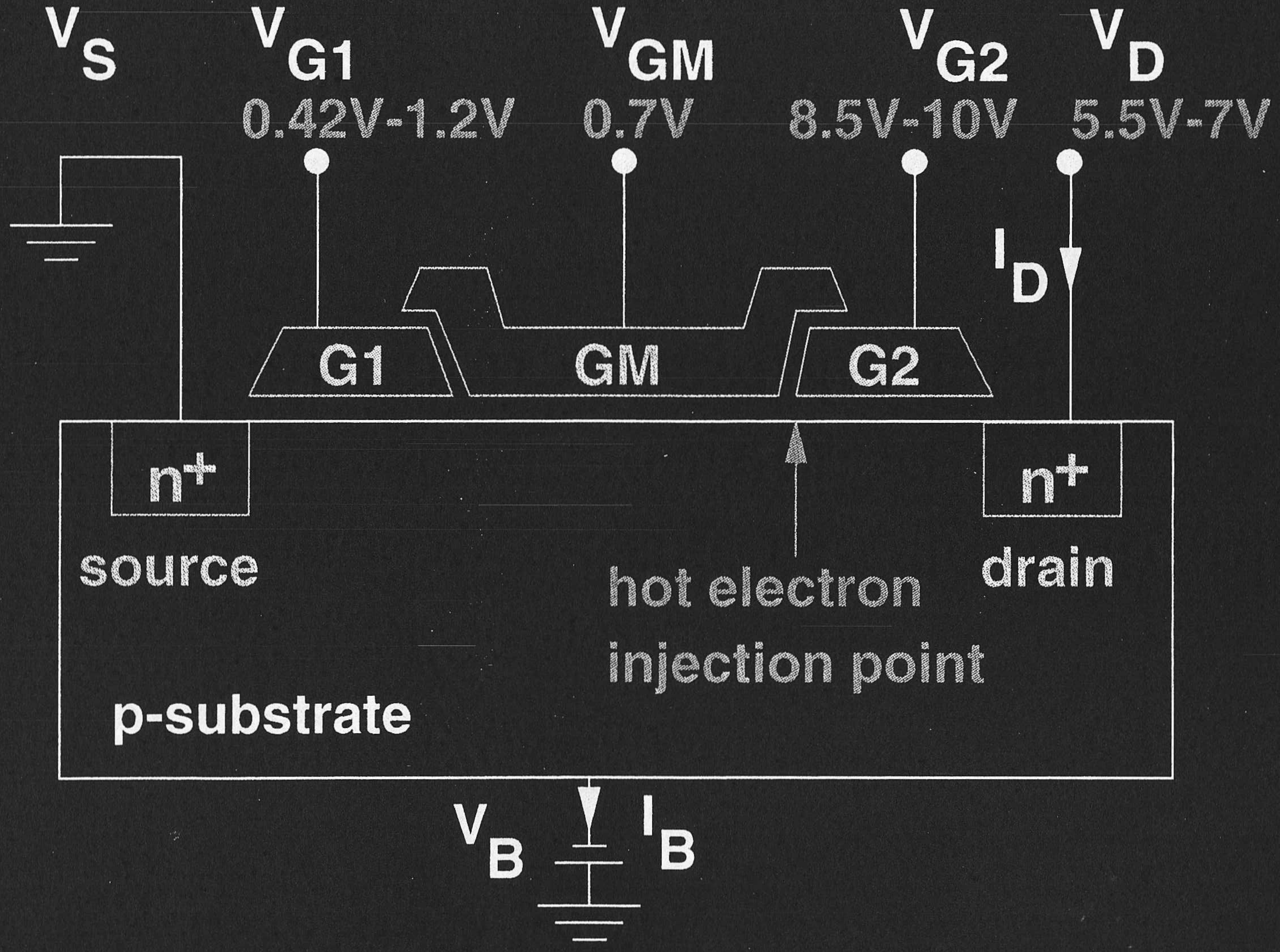
Fig. 6 Oscillograph illustrating the defect revealed by frame-transfer mode testing of the TDI-CCD.



SC-CCD

Merrill [IEDM 78]

Triple-gate MOSFET:
controls ID, Ex, Ey independently



Gate Current Injection: Lucky Electron Model

- $I_{G2}/I_D = C_1 \exp(-\phi_b/q\lambda E_m)$
- $I_B/I_D = C_2 \exp(-\phi_i/q\lambda E_m)$

ϕ_b = effective energy barrier for electron injection

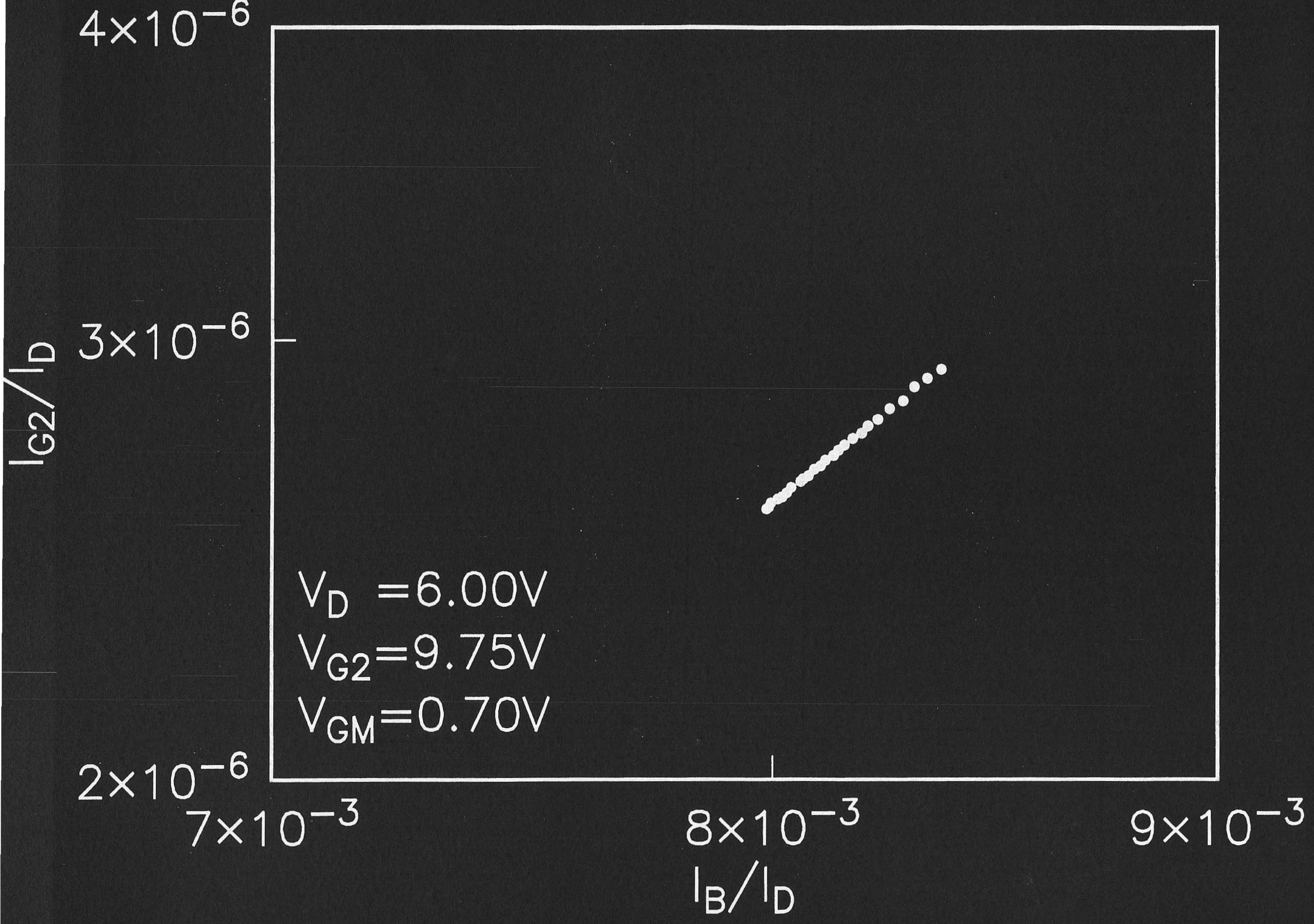
$\phi_i = qB_i\lambda$ = impact ionization energy

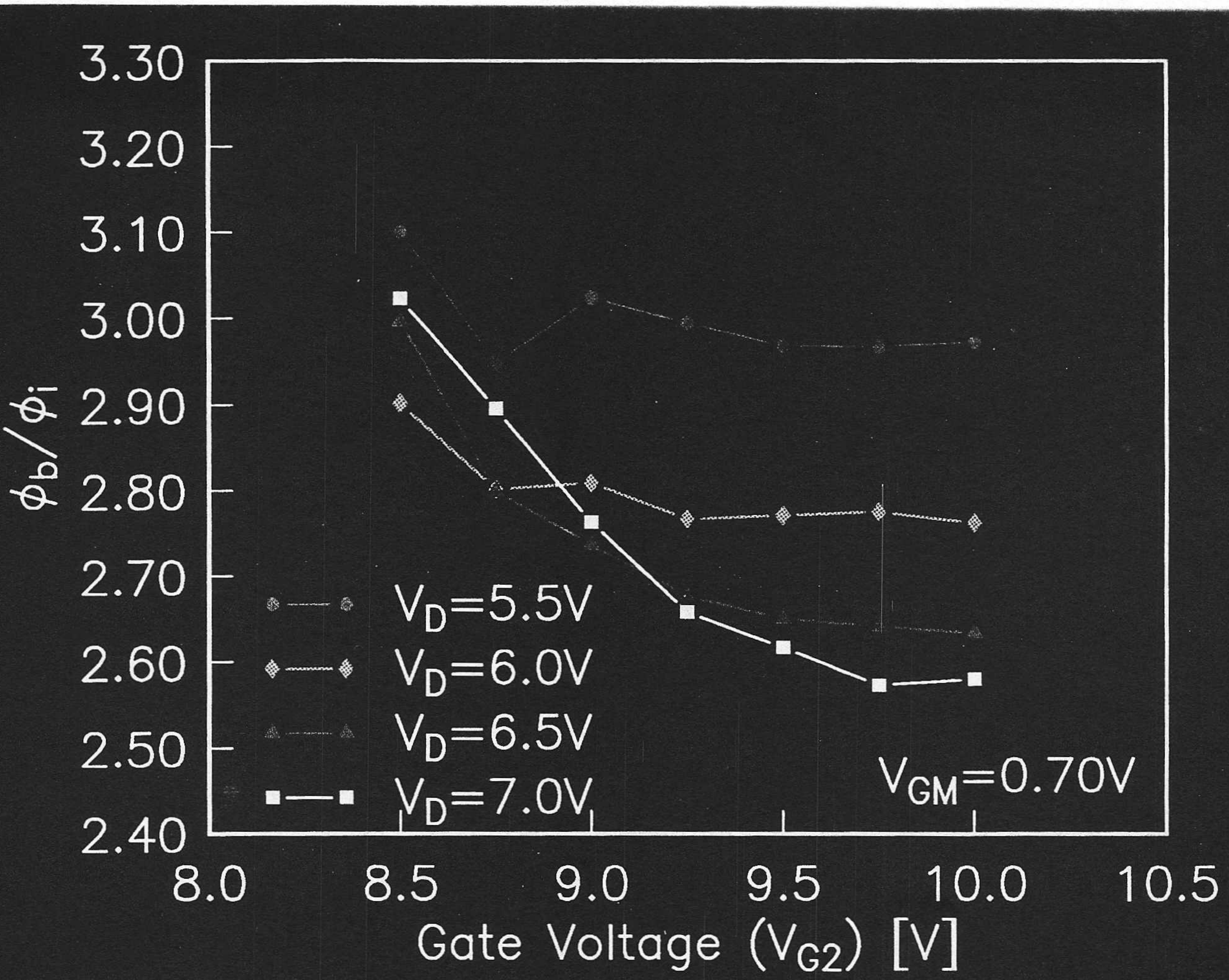
B_i = impact ionization threshold field

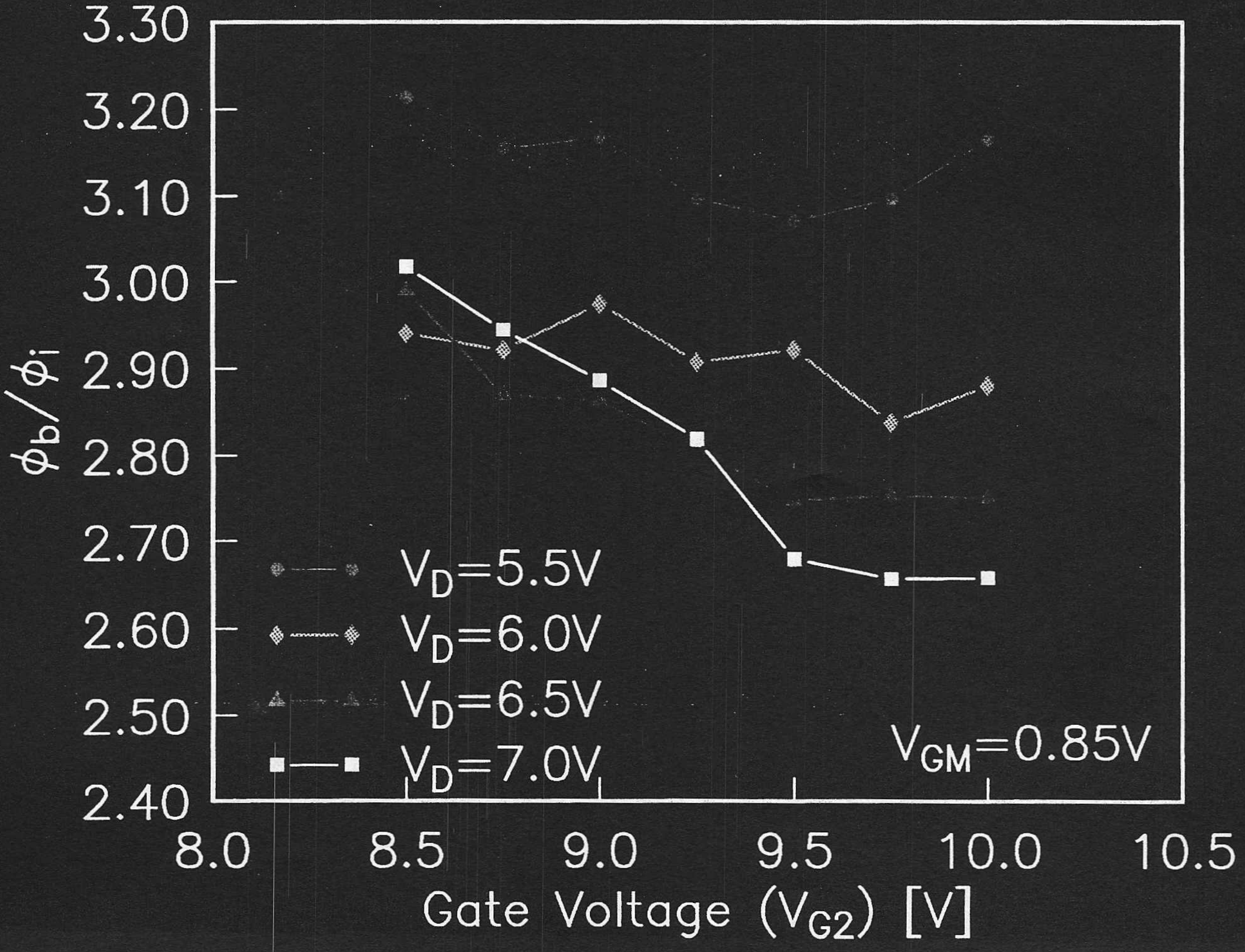
λ = hot–electron mean free path

Eliminate λE_m:

- $I_{G2}/I_D = C_3 \, (I_B/I_D)^{\phi_b/\phi_i}$


4×10⁻⁶
3×10⁻⁶
2×10⁻⁶
I_{G2}/I_D
7×10⁻³
8×10⁻³
9×10⁻³
I_B/I_D
V_D =6.00V
V_{G2}=9.75V
V_{GM}=0.70V


3.30
3.20
3.10
3.00
2.90
2.80
2.70
2.60
2.50
2.40
ϕ_b/ϕ_i
8.0
8.5
9.0
9.5
10.0
10.5
Gate Voltage (V_{G2}) [V]
V_D=5.5V
V_D=6.0V
V_D=6.5V
V_D=7.0V
V_{GM}=0.70V


3.30
3.20
3.10
3.00
2.90
2.80
2.70
2.60
2.50
2.40
ϕ_b/ϕ_i
8.0
8.5
9.0
9.5
10.0
10.5
Gate Voltage (V_{G2}) [V]
V_D=5.5V
V_D=6.0V
V_D=6.5V
V_D=7.0V
V_{GM}=0.85V