Low Noise Avalanche Photodiodes

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Talk Outline

- APD background
- Low noise mechanisms in thin p^+-i-n^+s
- Temperature dependence
- APD speed
- Conclusions

National Centre for III-V Technologies, University of Sheffield, UK

- ★ Established in Department of Electronic & Electrical Engineering, University of Sheffield in 1978
- ★ ***Mission:*** To provide III-V wafers & devices to the UK academic community
- ★ ***Current Capability:*** 2 MBE, 3 MOVPE, Device Fabrication, Characterisation
- ★ ***Staff*:** 10 scientists, 6 technicians
- ★ ***Growth output:*** 750 wafers / year
- ★ ***Optical wafers & devices:*** Lasers, LEDs, VCSELs, RC-LEDs, waveguides, modulators, AFPMs, pins, APDs, Q-Dot lasers, Q-Cascade lasers
- ★ ***Electrical wafers & devices:*** HBTs, HEMTs, diodes

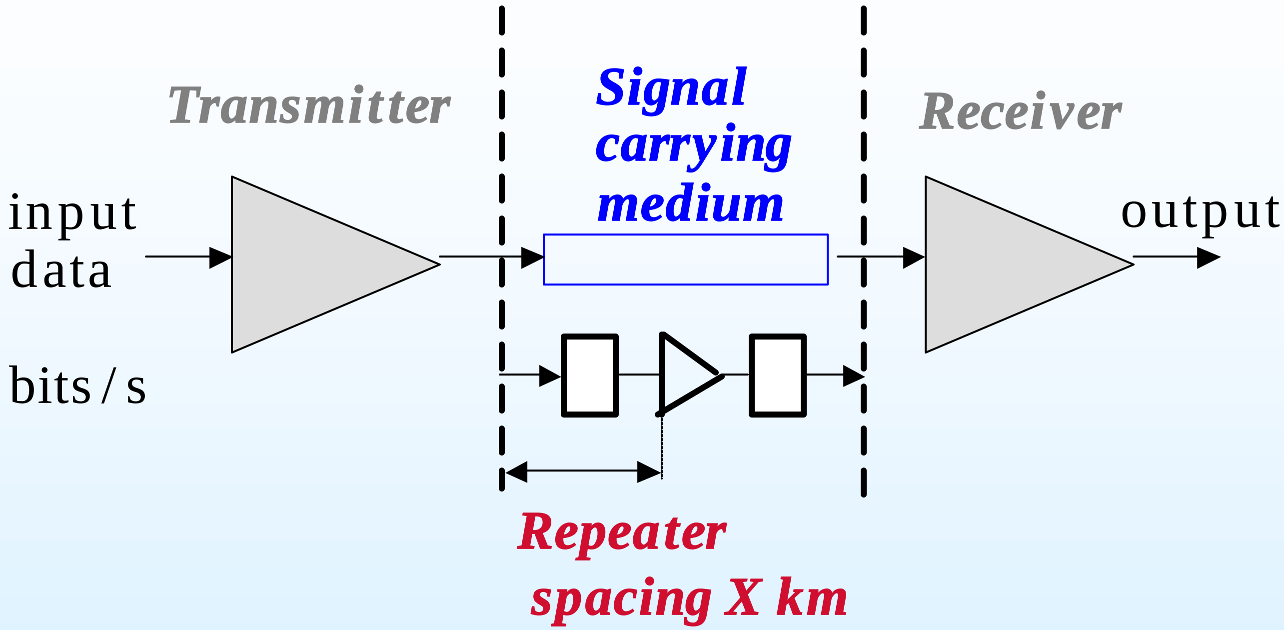
APD Research at Sheffield

Physics

- **Impact ionization coefficient investigation**
- **New materials and novel structures**
- **'Dead-space' characterization**
- **Excess noise measurements**
- **Temperature dependence**
- **Analytical and numerical modelling**
- **Low-noise, high-speed avalanche photodiodes**
- **Single photon avalanche photodiodes (SPADs)**

Devices

Generic communication system

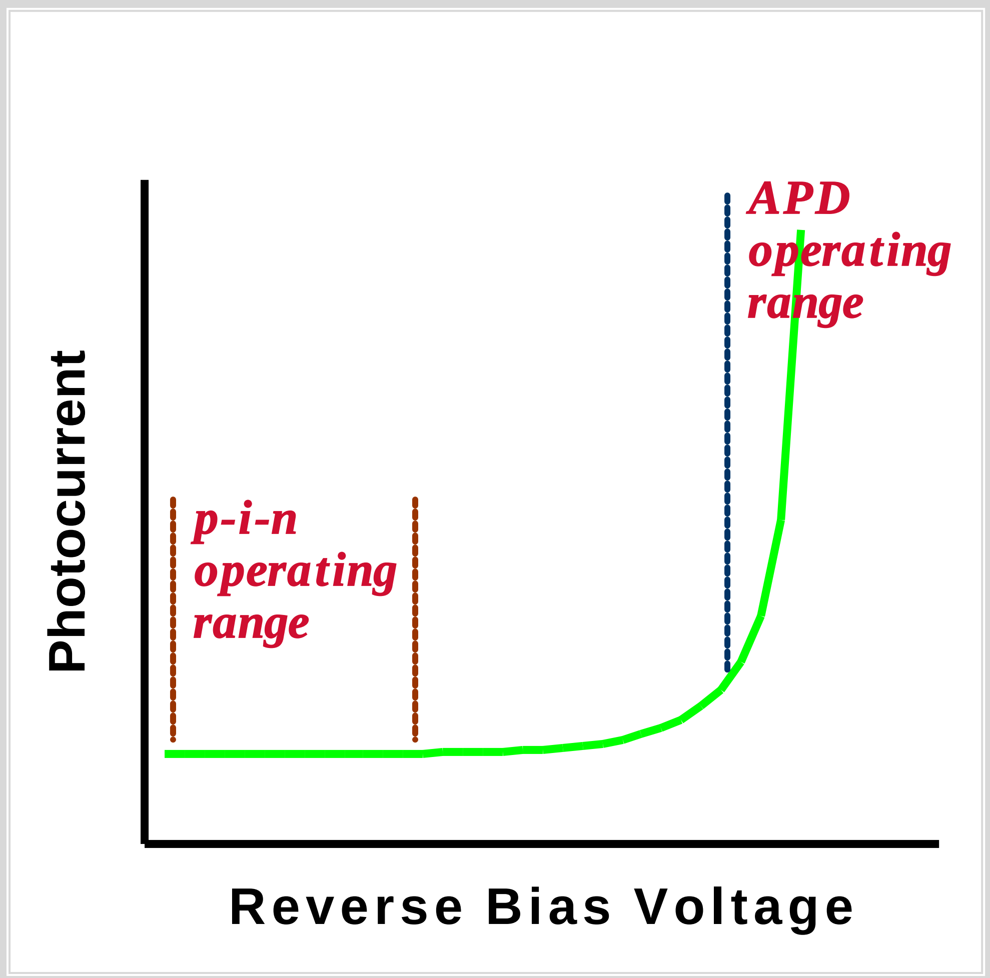


Communication capacity - Bit rate length product

= repeater spacing*data rate {X [km]*Bandwidth [b/s]}

Using an APD can increase repeater spacing

p-i-n vs. APD



p-i-n

- low voltage
- bias insensitive
- temperature insensitive
- simple bias circuit
- fast
- simple bias circuit
- cheap

APD

- high sensitivity
- single photon detection (possibility)

Technology Comparison

Photomultipliers

+ High gain (~10^6)
+ Low dark current
+ Low noise
? Reliability

- Expensive
- Poor efficiency
- Complex filters
- Bulky
- Fragile
- High voltage (~1kV)

Avalanche photodiodes

+ Inexpensive
+ Compact
+ Rugged
+ High detectivity
+ High reliability
+ Simpler, cheaper filters
+ Reasonable gain
+ High efficiency
+ Low voltage (<100V)

- High noise
- Temperature sensitive

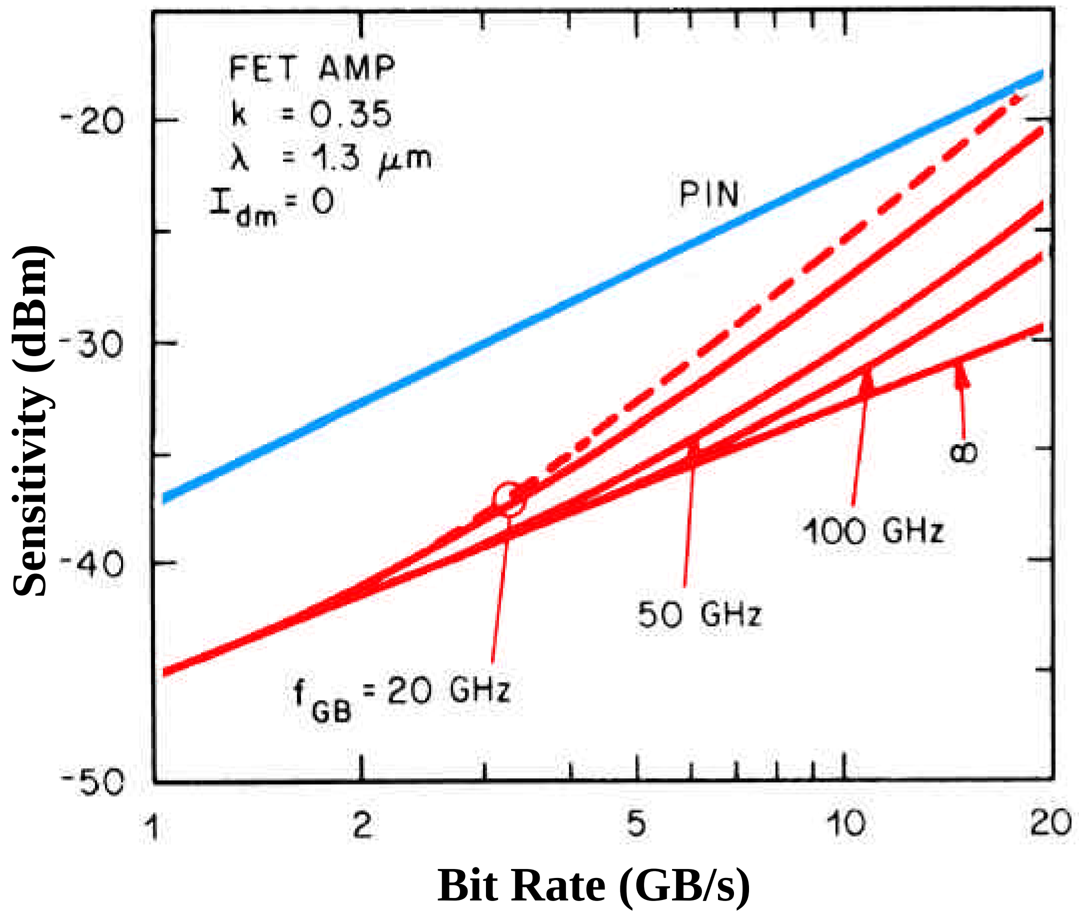
Comparison of three detector types

	PIN-FET	**Ge APD**	**InGaAs APD**
Sensitivity	**X dBm**	**(X+4) dBm**	**(X+8) dBm**
Cost	**Moderate**	**Moderate**	**High**
Wavelength	**1.3μm & 1.5μm**	**1.3μm**	**1.3μm & 1.5μm**
Reliability	**10^{11} hrs**	**10^{6}hrs**	**10^{6}hrs**

- ***An InGaAs APD requires 8dB less optical power to produce the same signal as a PIN-FET.***
- ***PIN-FET is cheaper, faster and more reliable.***

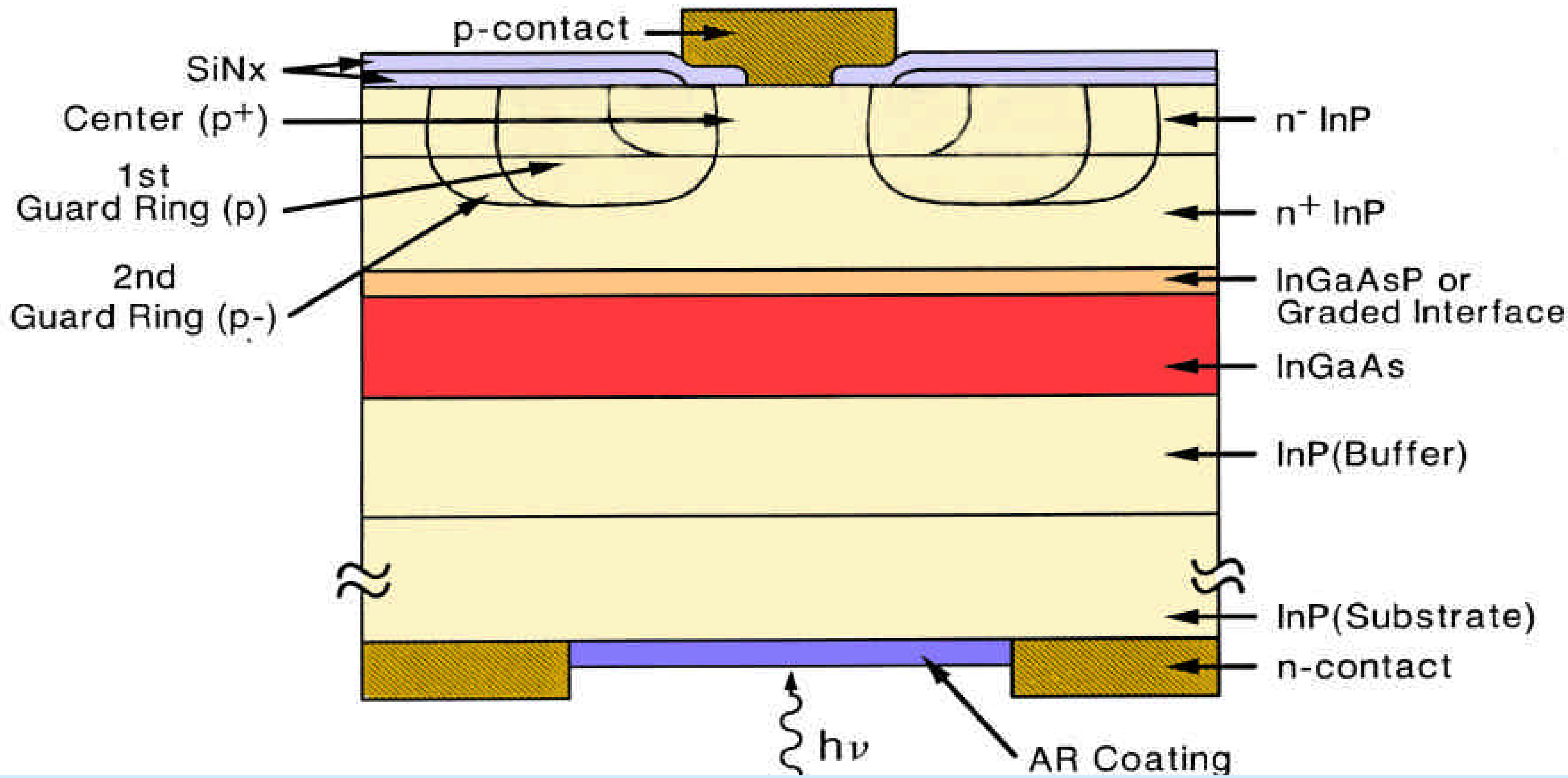
p-i-n vs. APD

Comparison of sensitivity

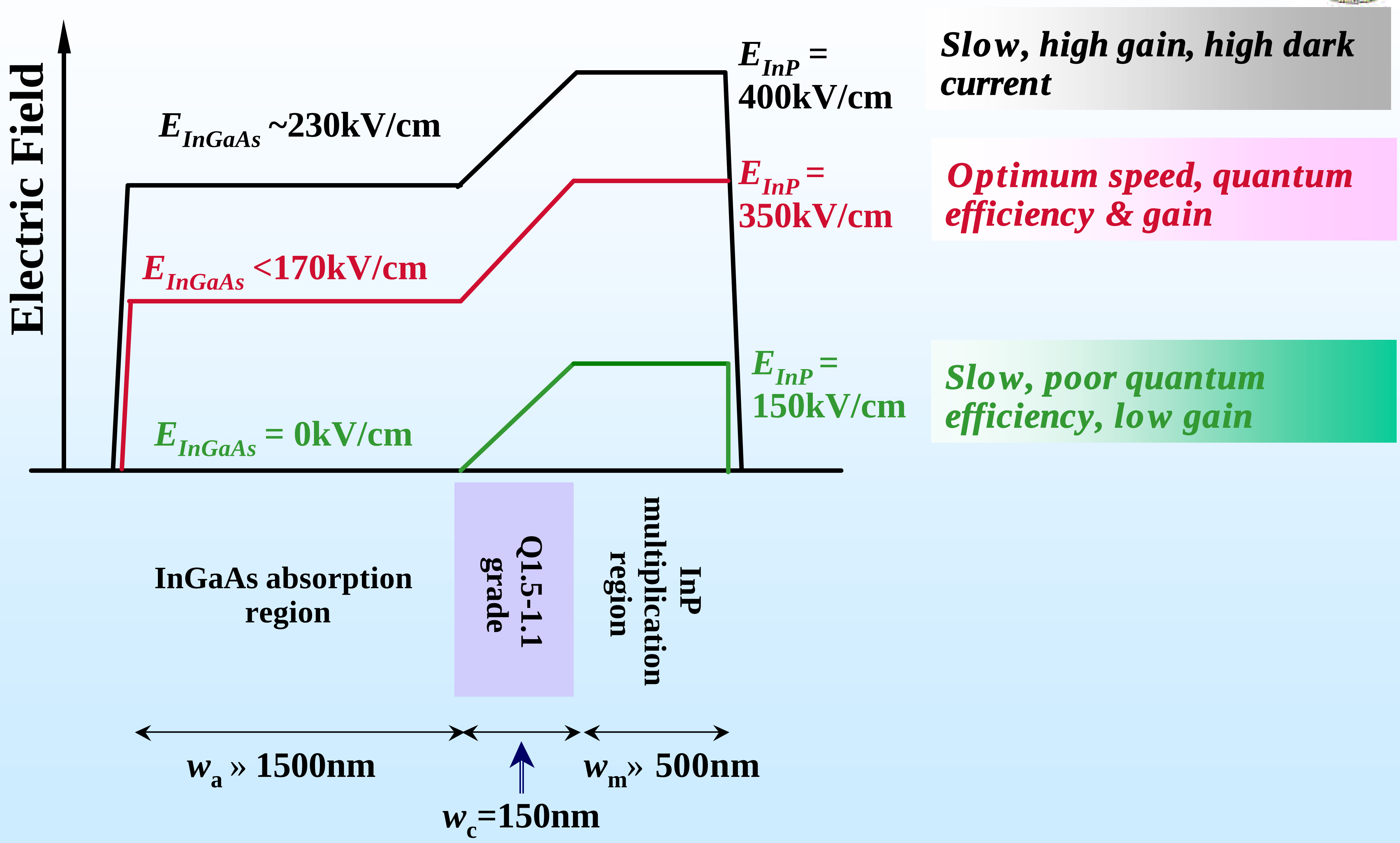


- ***APDs can have an extra -8dBm sensitivity c.f. p-i-n***
- ***APD advantage reduces as speed increases***

InGaAs/InP SAM-APD

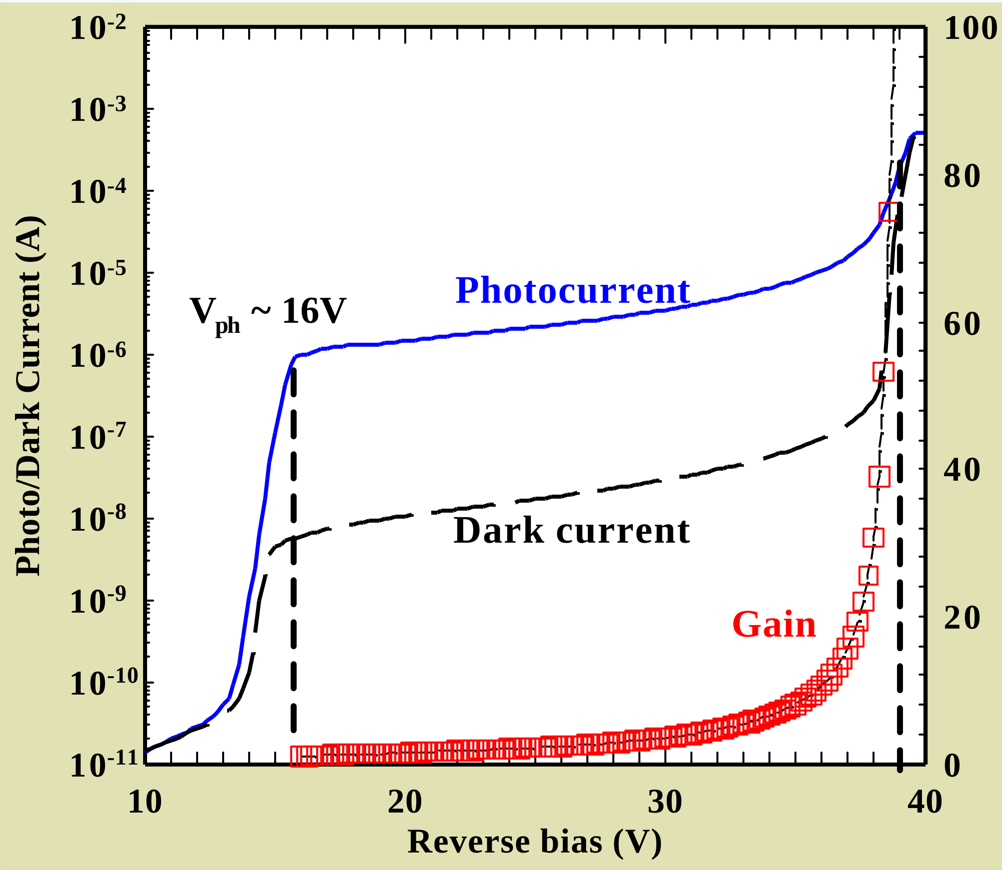


Electric field distribution in a SAM-APD



SAM-APD Current-Voltage Characteristics

Photocurrent and dark current



Punch-through ~ 16V
Breakdown ~ 39V

Low dark current even at high multiplication gains (> 50) (< 70nA @ 0.9 V_{bd})

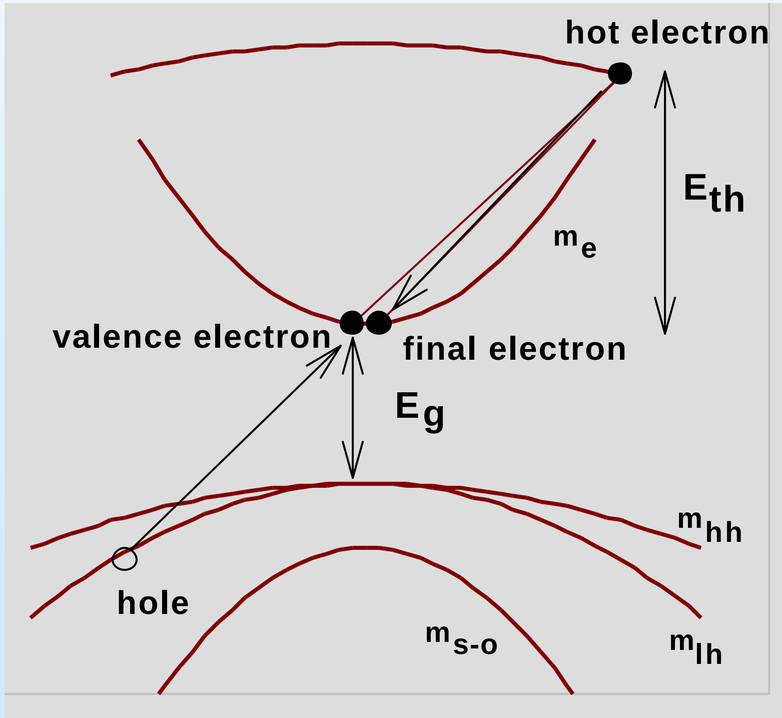
APD Vendors

Vendors	Sensitivity (dBm)	V_{BD} (V)	ΔV_{BD} (V/°C)	3DB bandwidth (GHz)	Misc:
JDSU ERM577	-32	40-70		1.8	10nA@ V_{BD} -1.5 8.5uA/uW@ V_{BD} -1.5
Mitsubishi FU319SPA	-33	35-75	0.12	1.9	
Agere P173A	-34	45-70	0.07-0.14	2	
Fujitsu FRM5W232BS	-34	50	0.12	2.5	
Nova Crystals NVR251	-	29-32	0.03		Fused InGaAs/Si
NEC 8501		40-80	0.1	3	7nA@0.9 V_{BD}
Alcatel 1914		30-75		3.5	70nA@0.9 V_{BD}
Sensors Unlimited SU-10ATR	-24	25-42		6	5nA@ V_{BD} -1
Mitsubishi FU321SPA	-25	20-40	0.05	7	
JDSU ERM578	-22	20-40		7	
NEC 4270	-25	16-32	0.02	8	Superlattice APD (k=0.4)

Ionization - Threshold energy

For ionization:
1) **energy and momentum conservation**
2) **minimisation of energy**

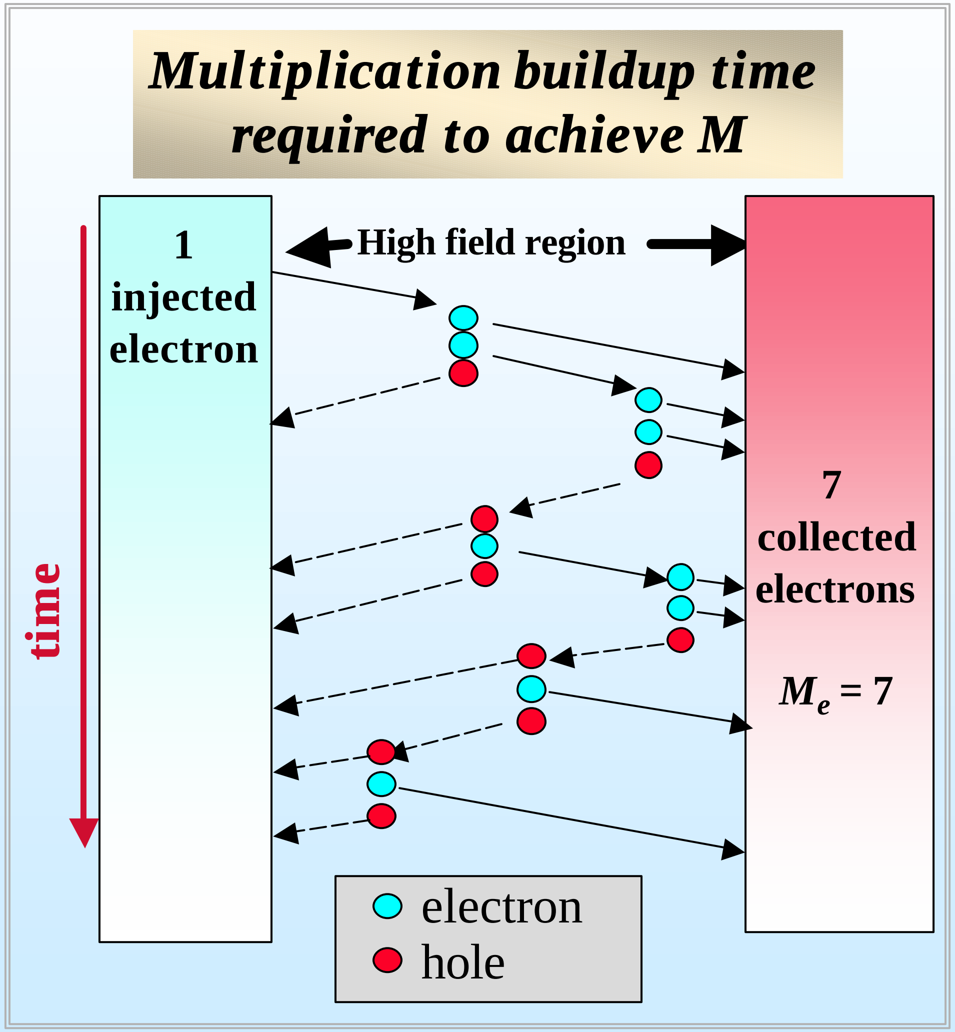
Impact ionization schematic diagram



E_g = Band gap
E_{th} = Threshold energy 'minimum energy for ionization'

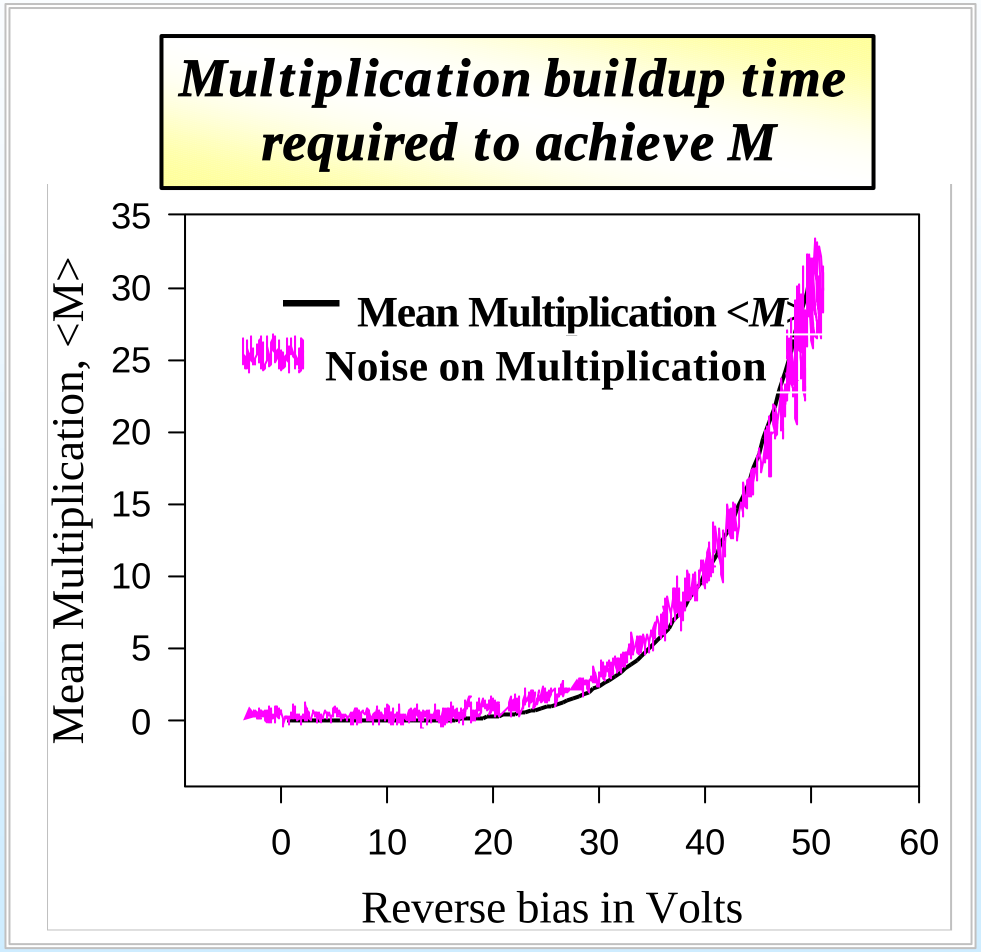
For parabolic bands and equal masses, $E_{th} = 1.5\ E_g$

Multiplication process



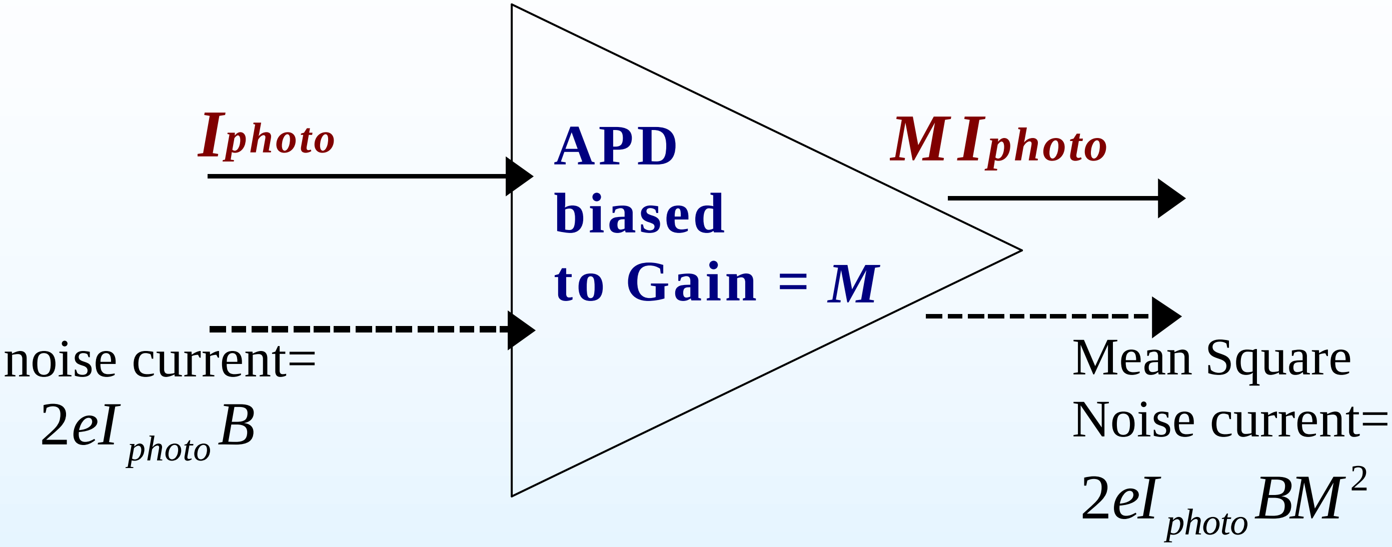
- Multiplication= current out/current in
- Avalanche takes time to build-up

Excess avalanche noise



- ***An APD can give us gain.***
- ***Unfortunately the avalanche noise can degrade the S/N ratio.***
- ***An optimum value for <M> exists.***

An ideal avalanche photodiode



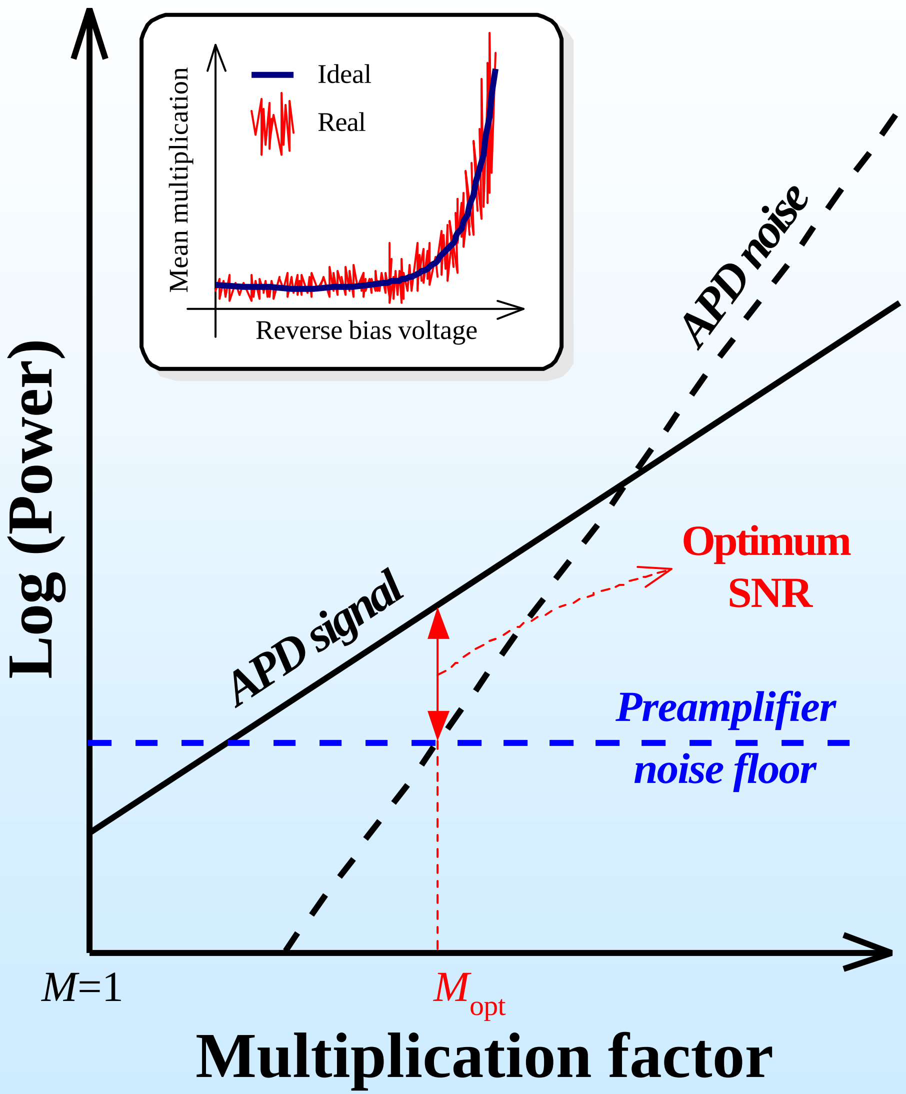
- **Non ideal APD**

  $$S = 2eI_{photo}BM^2 F$$

  where F = excess noise factor

- **For an ideal APD F = 1**

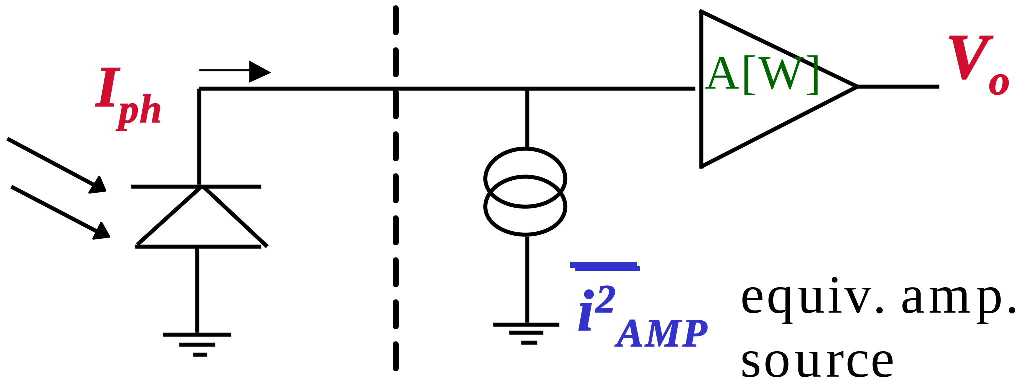
Background



- **APD's rely on *internal gain* to improve S/N ratio**
- **Impact ionization process Þ *stochastic* Þ avalanche noise**
- **Excess avalanche noise limits APD's maximum useful gain, *M***
- **In bulk structure, large b/a (or a/b) ratio required for low excess noise**

Photodetectors - S/N

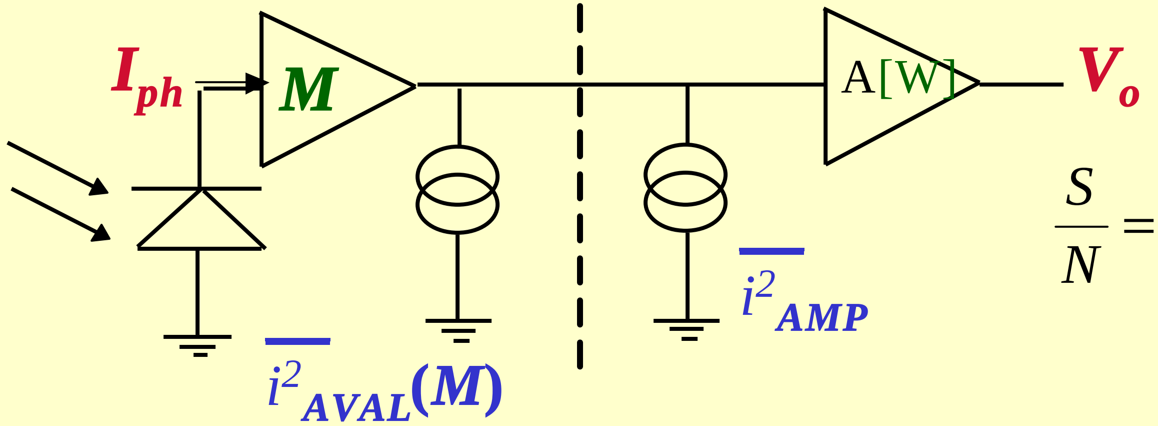
p-i-n photodiode and amplifier



equiv. amp. noise source

$$\frac{S}{N} = \frac{(I_{ph})^2}{(i_{amp})^2}$$

Avalanche photodiode and amplifier



$$\frac{S}{N} = \frac{(MI_{ph})^2}{i_{amp}{}^2 + i_{AVAL}{}^2}$$

McIntyre's avalanche noise theory (1966)

$$F(M) = M\left(1 + \frac{(1-k)}{k}\left(\frac{M-1}{M}\right)^2\right)$$

where $k = \dfrac{b}{a}$

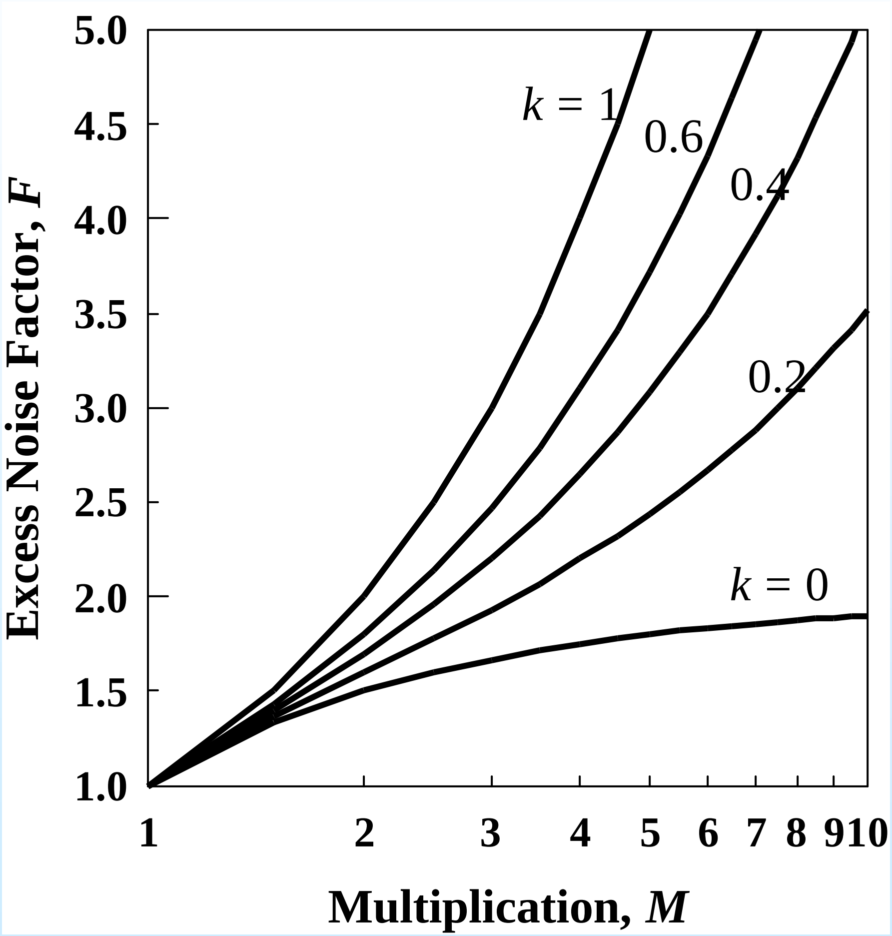
- ★ a = **electron probability of ionization per unit length [m^{-1}]**
- ★ b = **hole probability of ionization per unit length [m^{-1}]**

Assumes:

❶ **Multiplication process does not depend on carrier history.**

❷ $\boldsymbol{k}$ **=** b/a **is a constant**

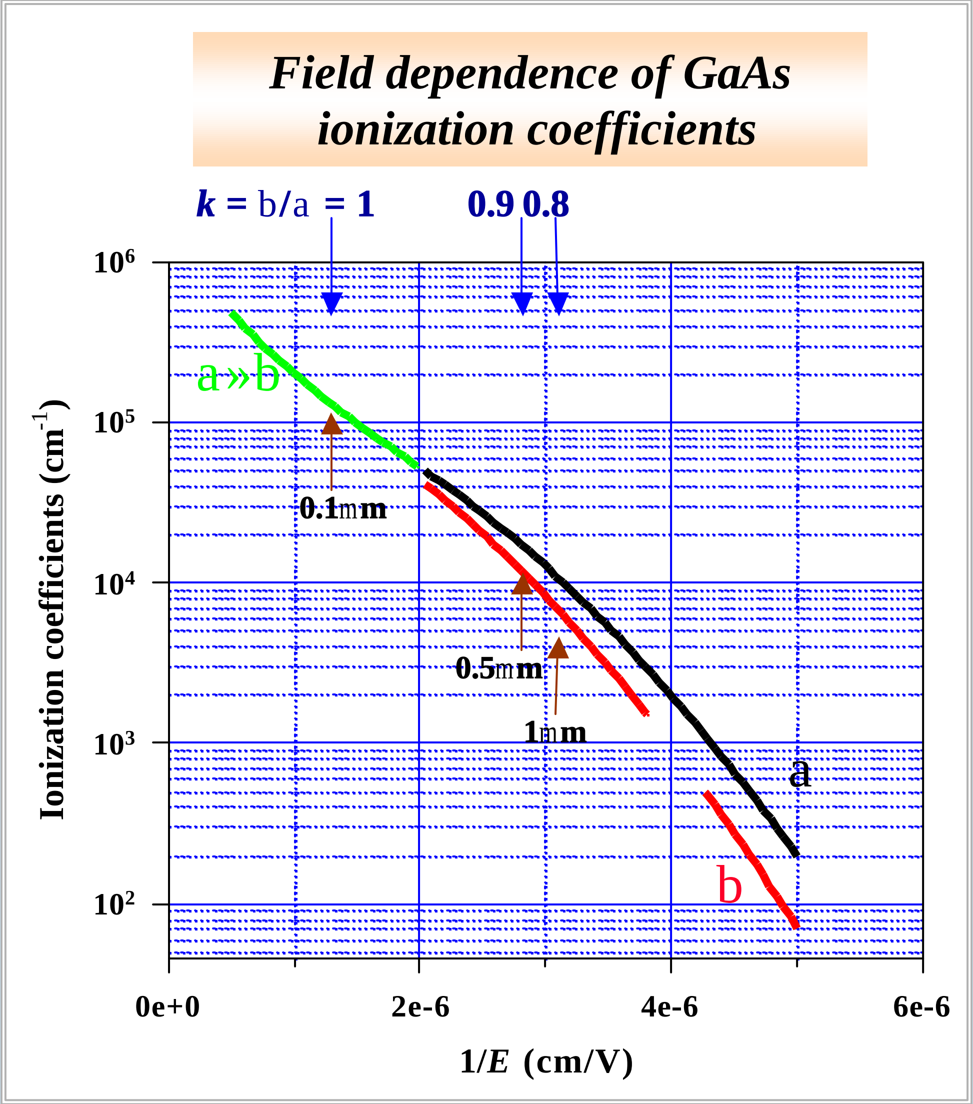
McIntyre's model for electron injection
F v M_e



k = b / a

The excess noise depends only on the ionization coefficient ratio (k) and the multiplication value. Larger ionizing carrier type should initiate avalanche.

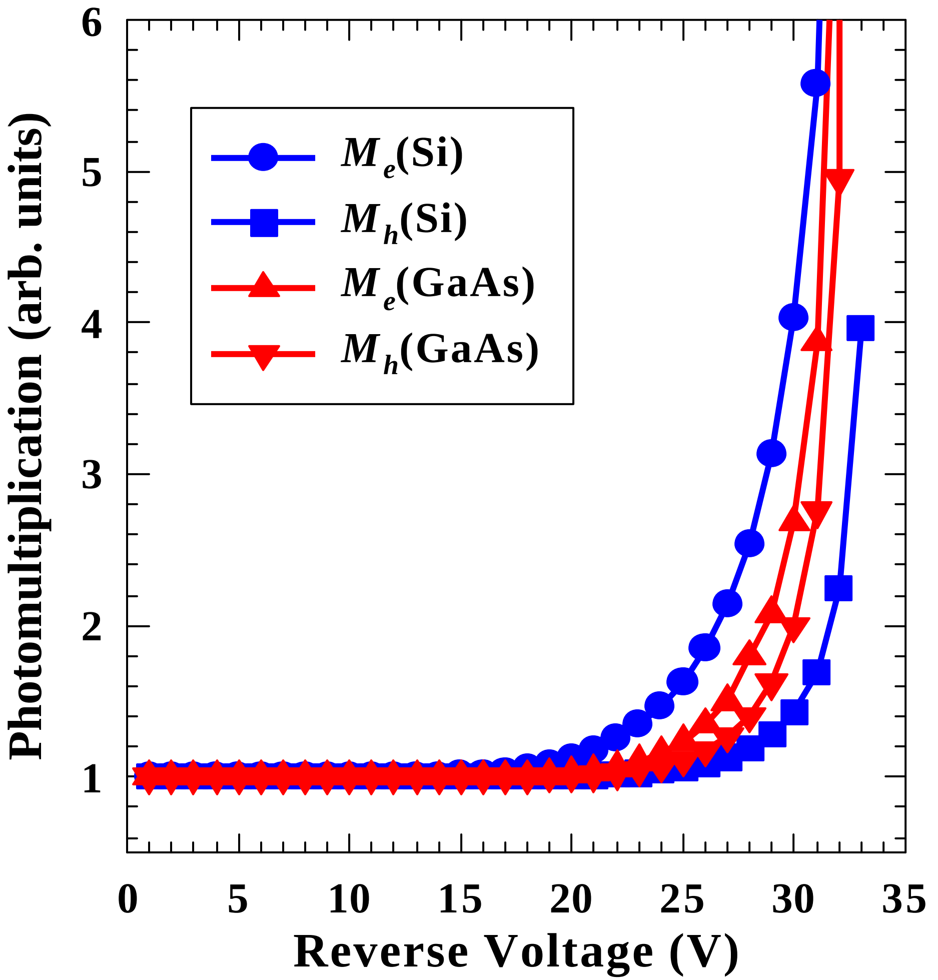
GaAs Ionization Coefficients



- ***Most III-V semiconductors have 0.4 £ k £ 2.5***
- ***High excess noise expected, especially at higher electric fields when k ® 1***

Ionization Coefficients

M_e and M_h for 1mm Si and GaAs pins



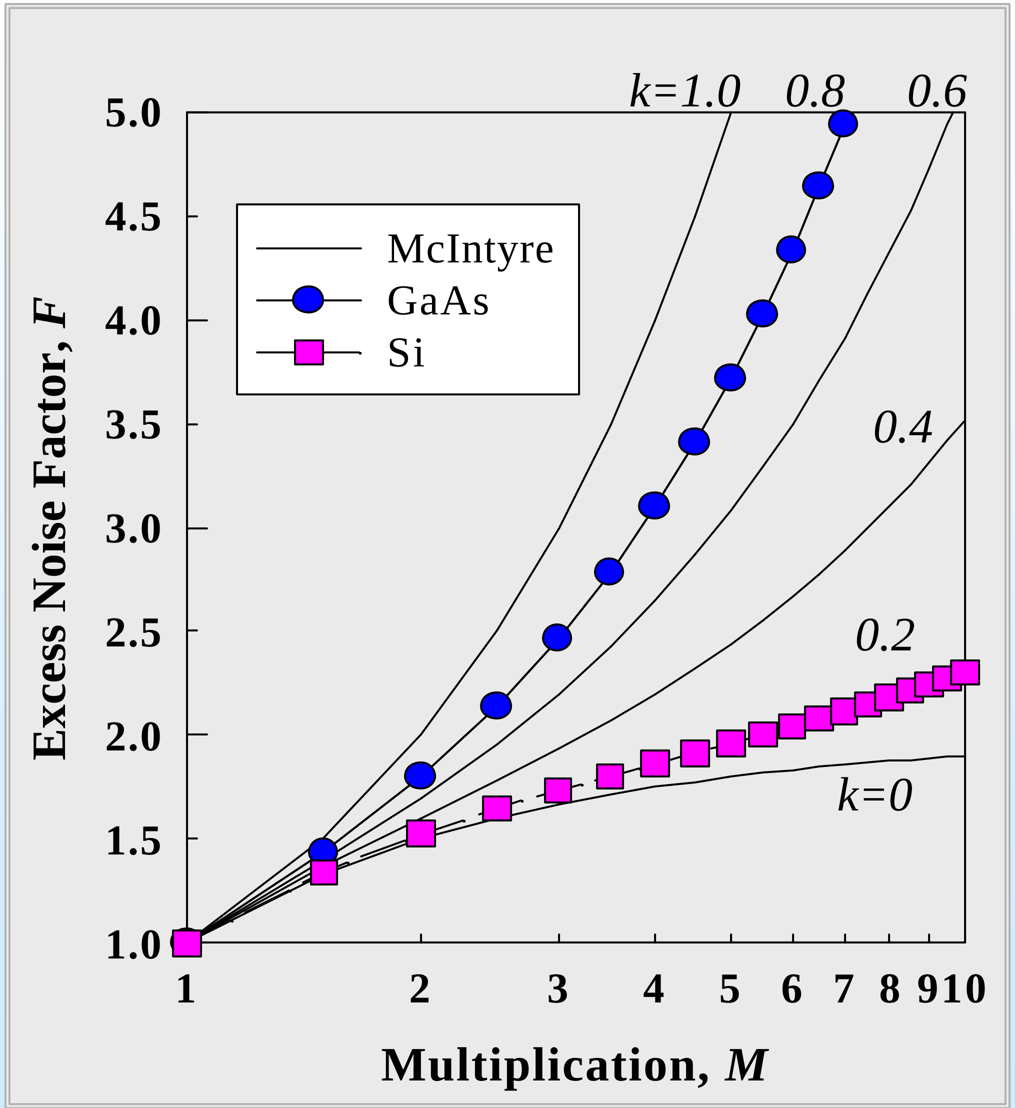
Simple relationship between a, b ***and multiplication characteristics in pins.***

$$\alpha = \frac{1}{W}\left[\frac{M_e - 1}{M_e - M_h}\right]\ln\left(\frac{M_e}{M_h}\right)$$

$$\beta = \frac{1}{W}\left[\frac{M_h - 1}{M_h - M_e}\right]\ln\left(\frac{M_h}{M_e}\right)$$

GaAs & Si have similar V_{bd} but very different a/b ***ratios.***

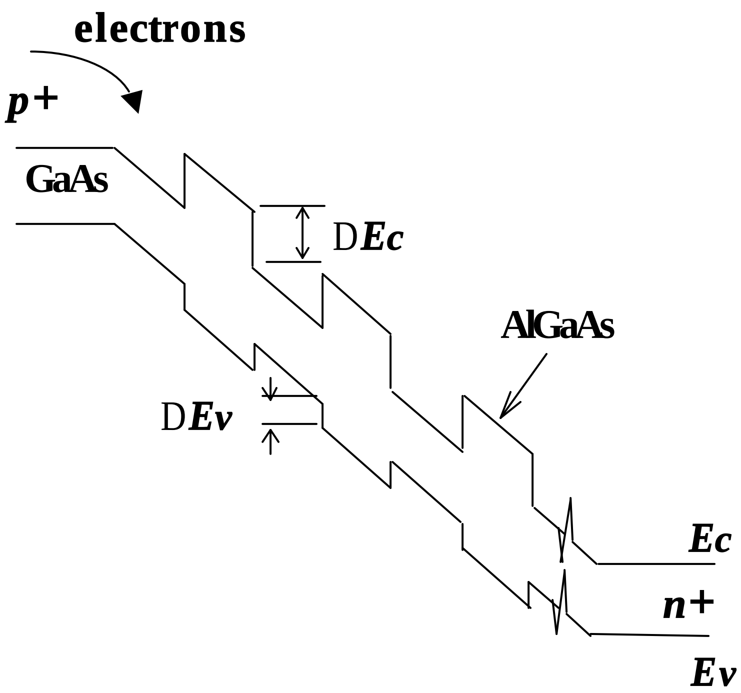
Excess noise in Si and GaAs, M_e



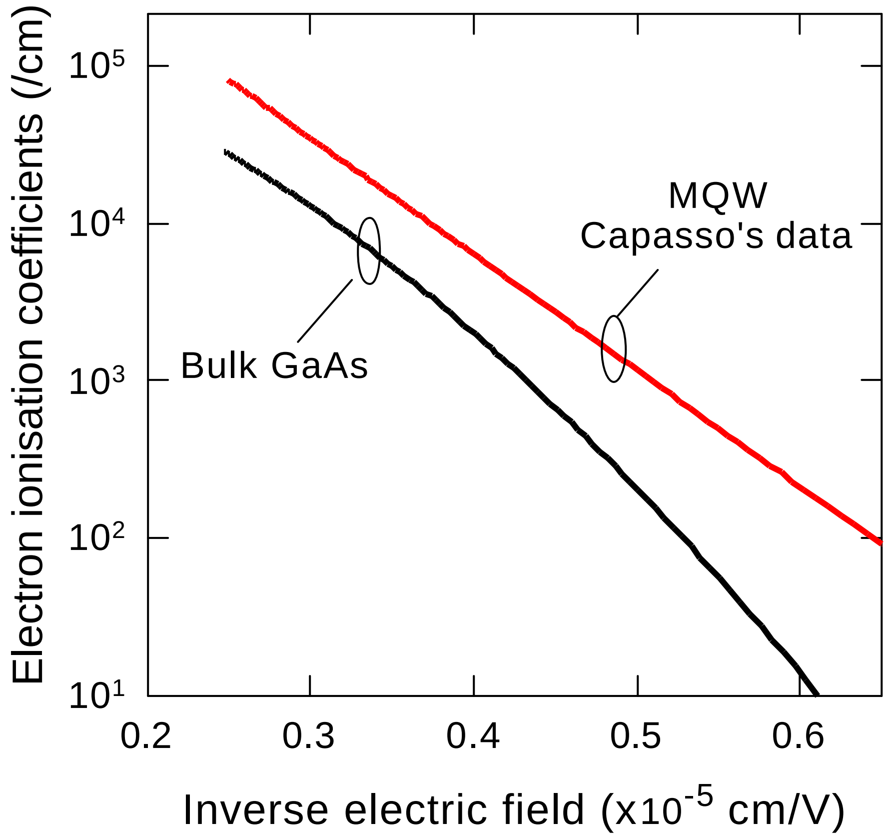
- **In thick structures, the excess noise *F* is determined by *k*, the b/a ratio.**
- **Silicon has a small *k* compared to GaAs, hence low noise.**

Enhancement of Ionization by MQW's

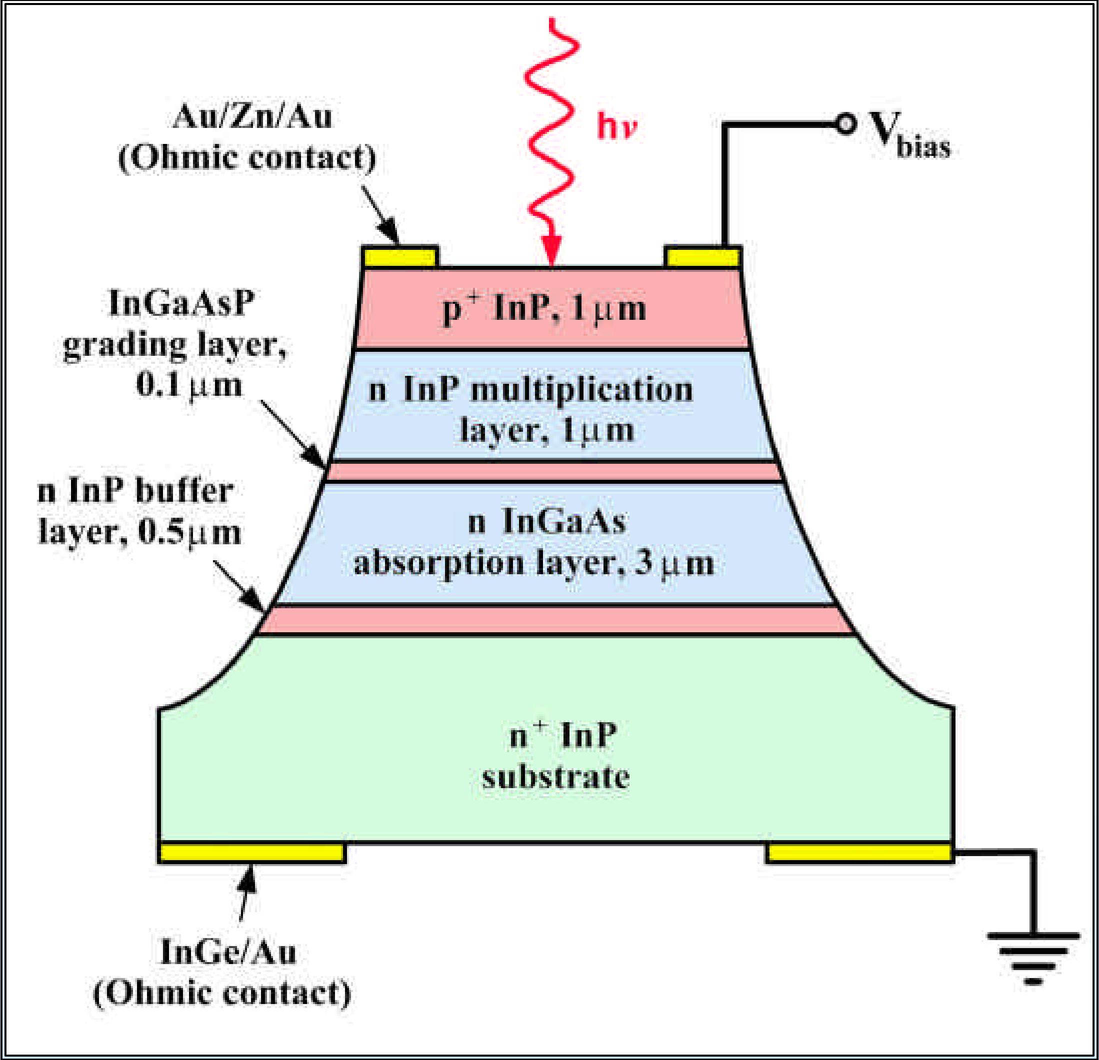
Chin et al. (1980) postulated that a large △*Ec* would enhance *a*



Capasso et al. (1982) reported a large enhancement in a ? in AlGaAs/GaAs MQW's

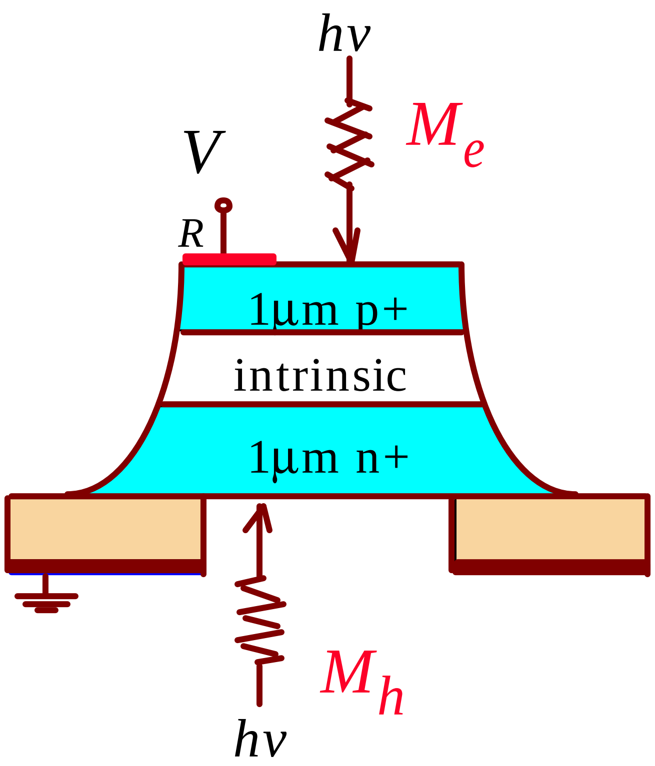


Schematic of a SAM-APD



- ***Light is absorbed in thick InGaAs layer***
- ***Photogenerated holes impact ionize in InP***
- ***Conventional designs involve thick multiplication layers, so that*** a/b ***ratio is small, to achieve low excess noise***

p-i-n diode schematic

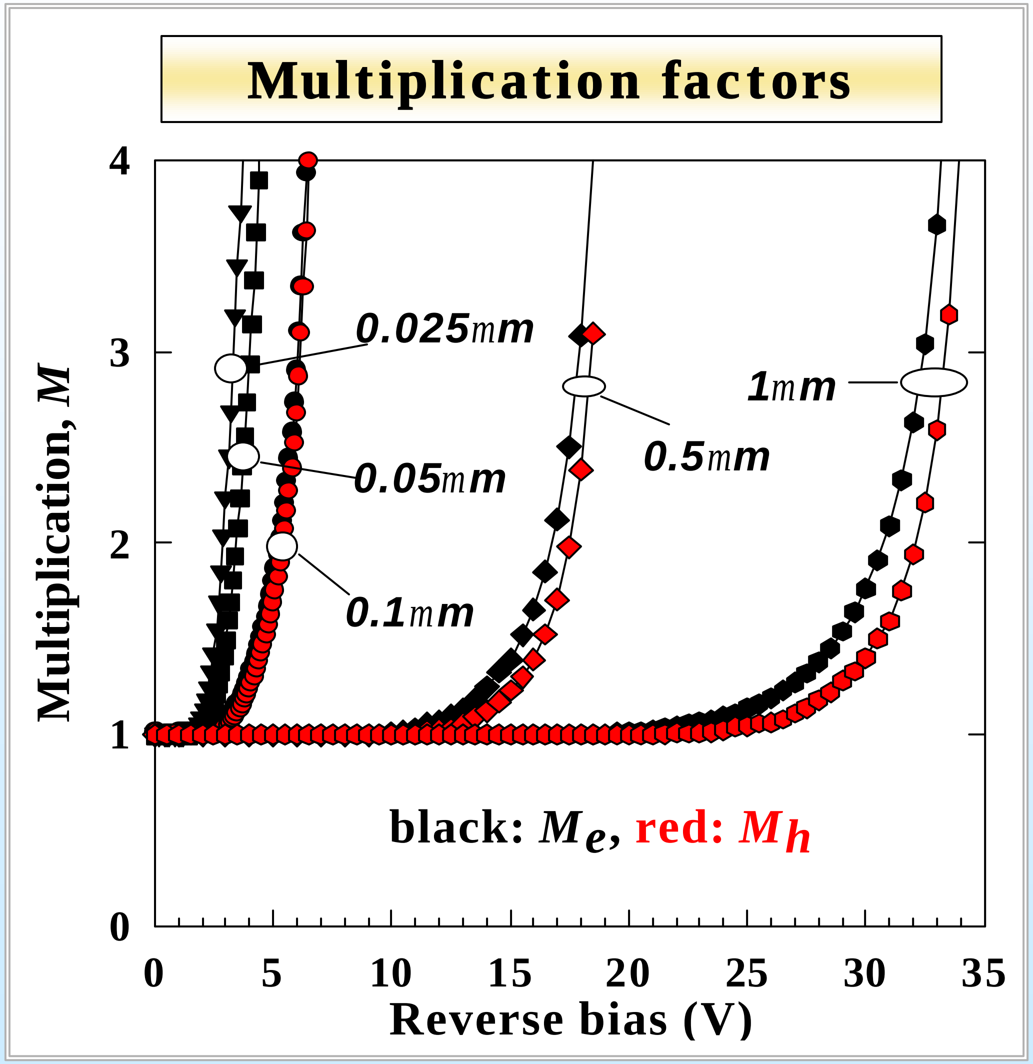


Intrinsic thickness, w varies from 1mm to 0.05mm.

Pure M_e & M_h obtained by illuminating thick p^+ & n^+ layers with short wavelength illumination.

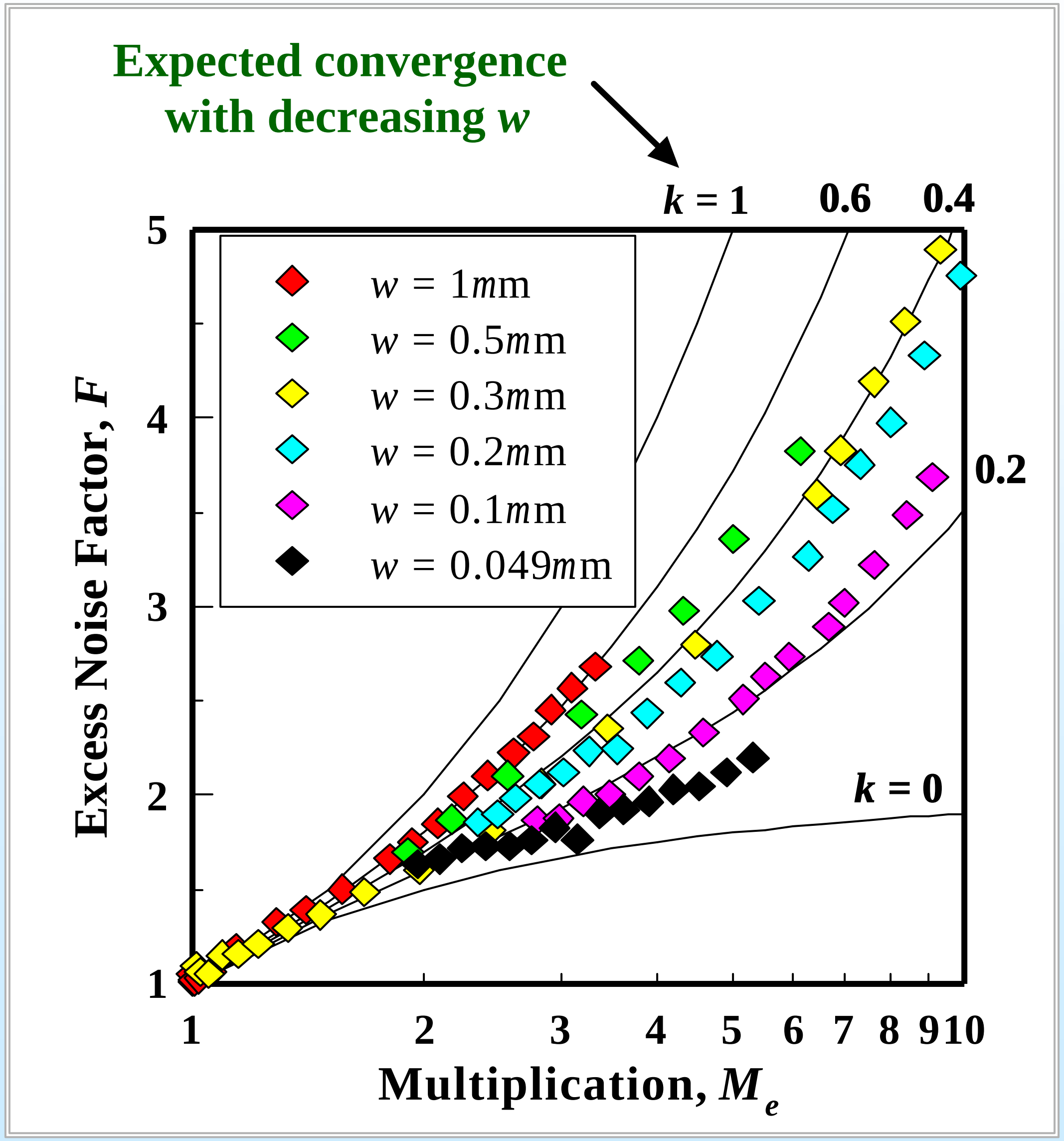
n^+-i-p^+ s also grown to obtain M_h more easily.

Multiplication from GaAs p^+-i-n^+s



- ***M_e and M_h were measured in different thickness p^+-i-n^+s.***
- ***Lock-in techniques allow M_e and M_h to be determined in the presence of large dark currents.***
- ***M_e » M_h as 'w' decreases, suggesting that*** a » b

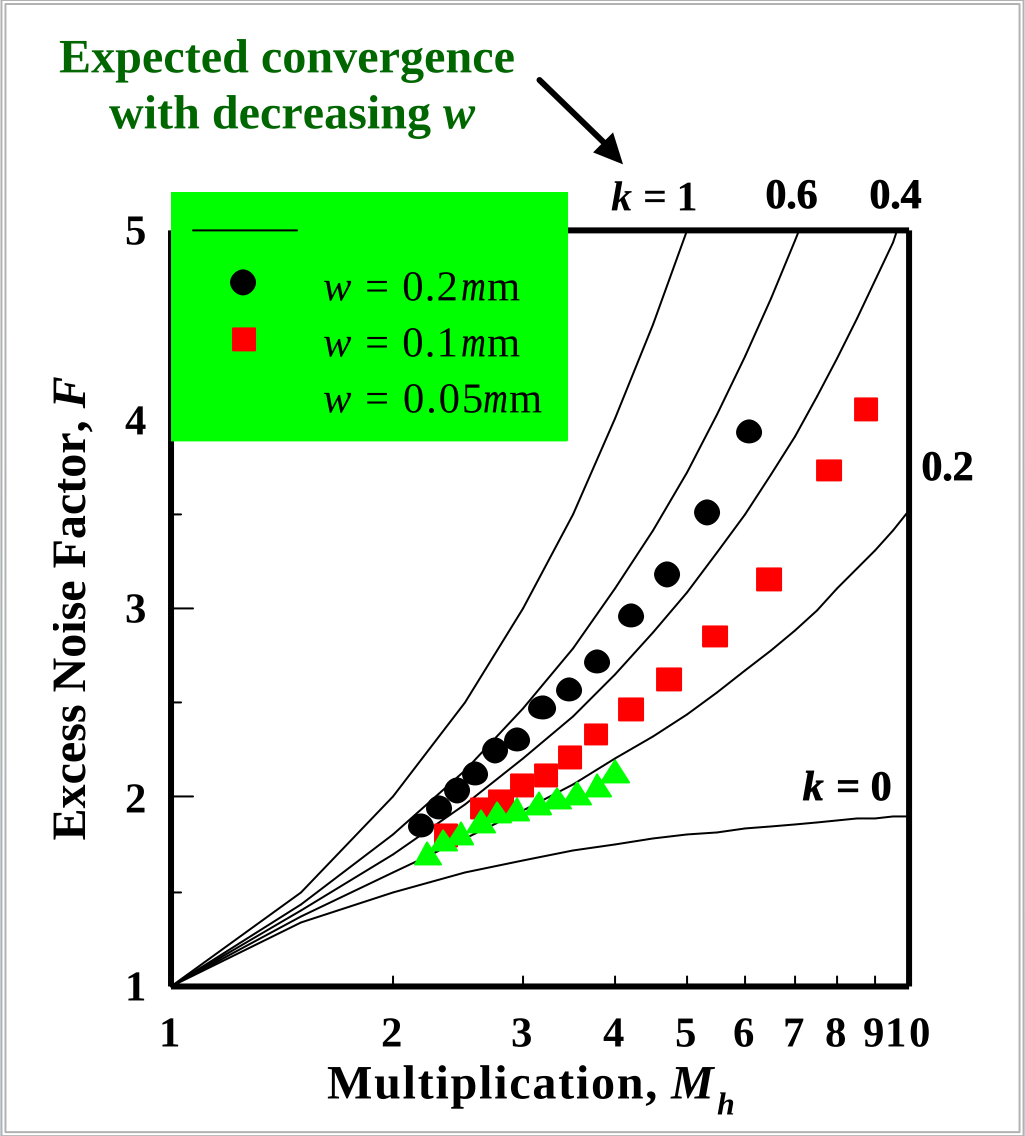
Excess noise in GaAs p^+-i-n^+s



Electron initiated noise measurements showed unexpected and significant noise reduction as w became smaller

The excess noise decreases as w decreases, instead of increasing as $k \rightarrow 1$

Excess noise in GaAs n^+-i-p^+s

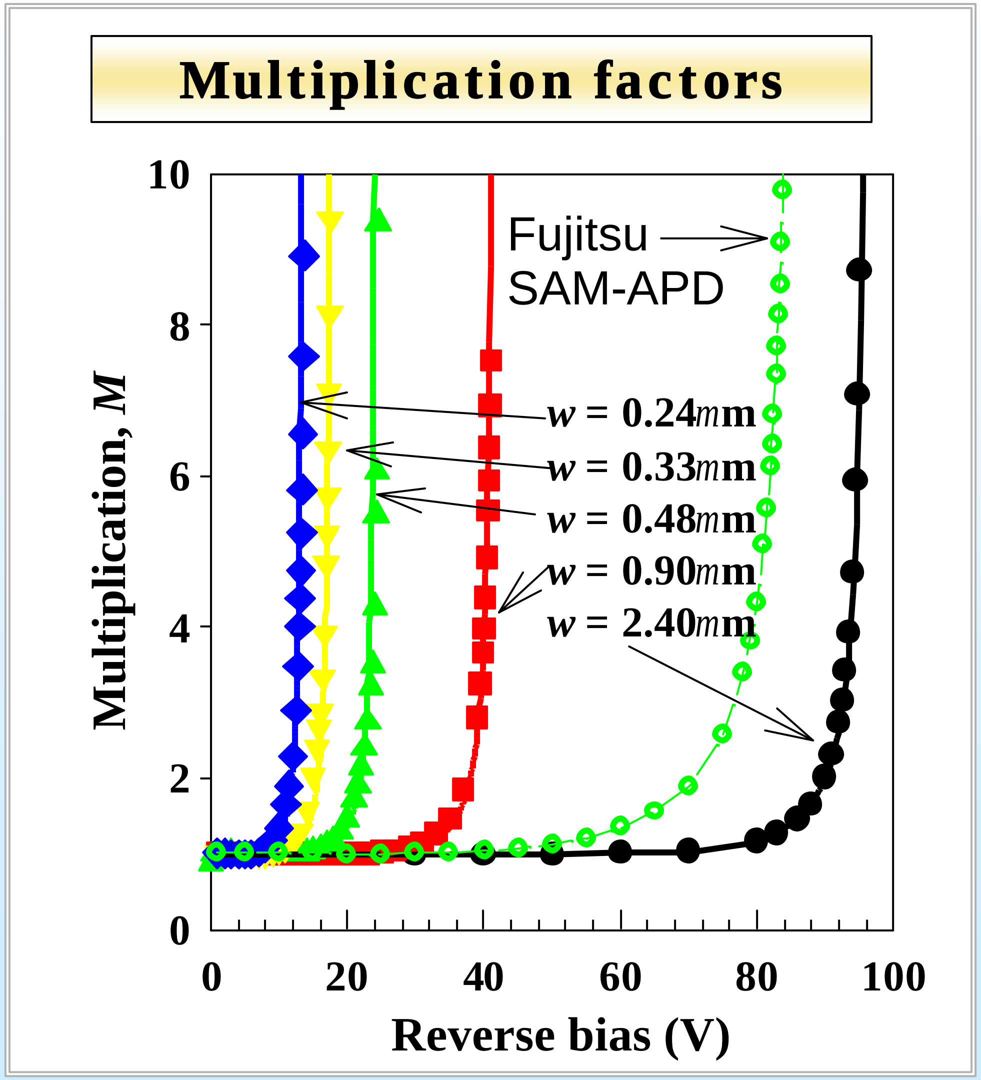


The excess noise *decreases* as *w* decreases, instead of increasing according to *k*.

Hole initiated noise measurements also showed unexpected and significant noise reduction as w became smaller

Behavior cannot be explained by McIntyre theory

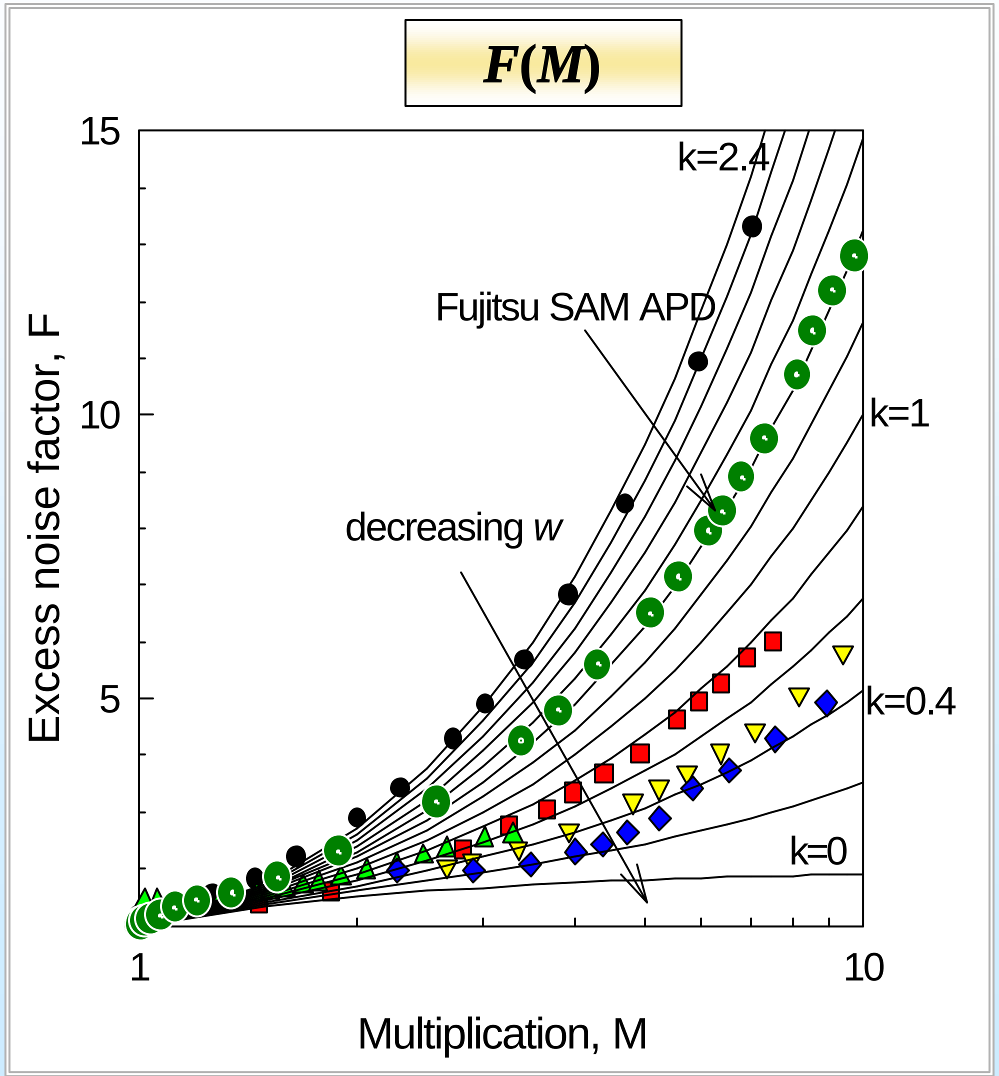
Multiplication characteristics in InP



Measured M_e (symbols)

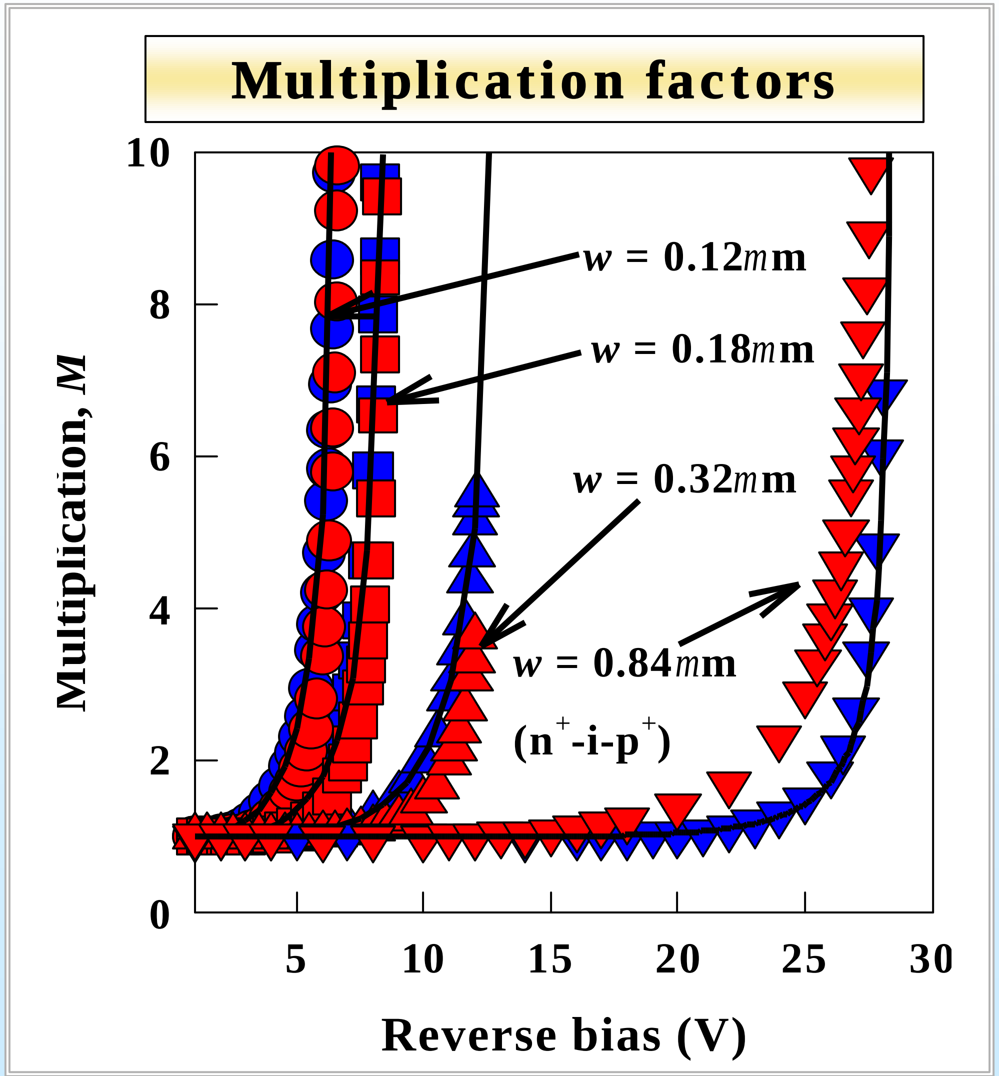
Calculated M_e (solid lines) using bulk ionization coefficients

Excess noise factor in InP



- **Same symbols as before**
- **Noise measured using wrong (electron) carrier type**
- **Fujitsu SAM-APD gives b/a = 1.4 \ k_{eff} = 0.7**
- **Structure with w = 0.24 gives k_{eff} = 0.4 - much better than SAM-APD with hole multiplication**
- **Low noise possible even with electron injection with thin *w***

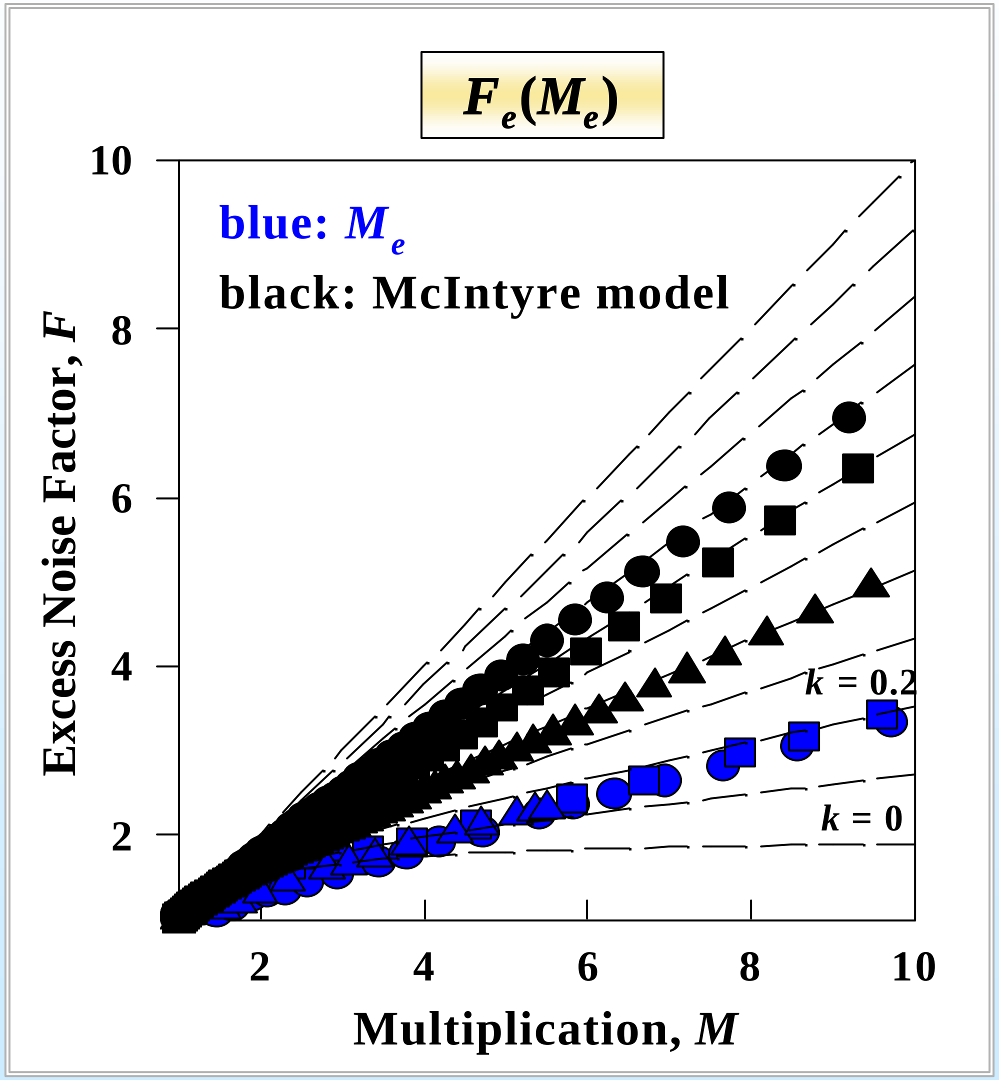
Multiplication characteristics in Silicon



Measurement of M_h and M_{mix} on 0.84μm n^+-i-p^+

Measurement of M_e and M_{mix} on 0.32, 0.18, 0.12μm p^+-i-n^+s

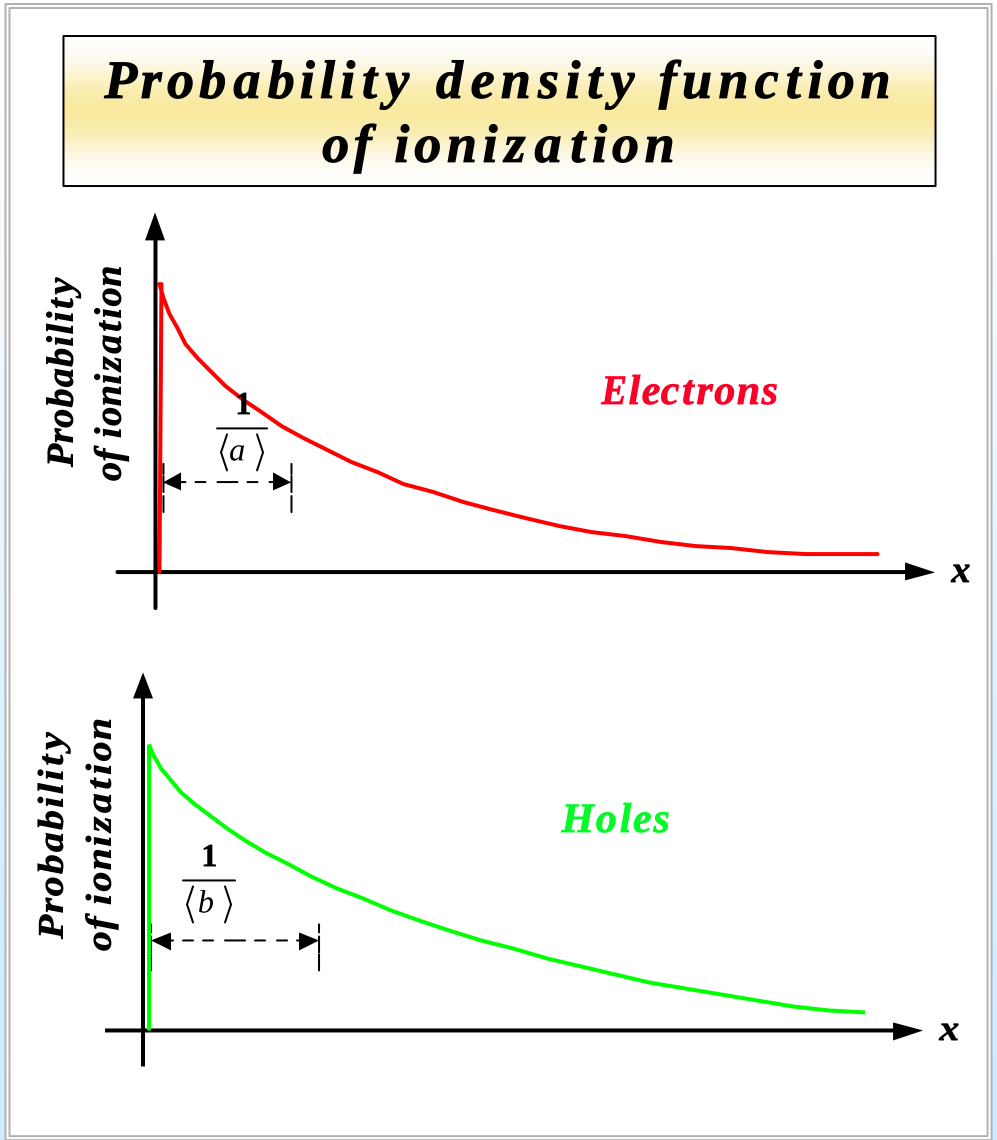
Local noise model prediction vs. experiment in submicron Si p^+-i-n^+s



- Local field noise model gives increasing excess noise from k = 0.4-0.7 as w decreases from 0.32-0.12mm.
- Experiment shows that $F(M_e)$ however is virtually constant at k » 0.2.

Modeling of thin APD behavior

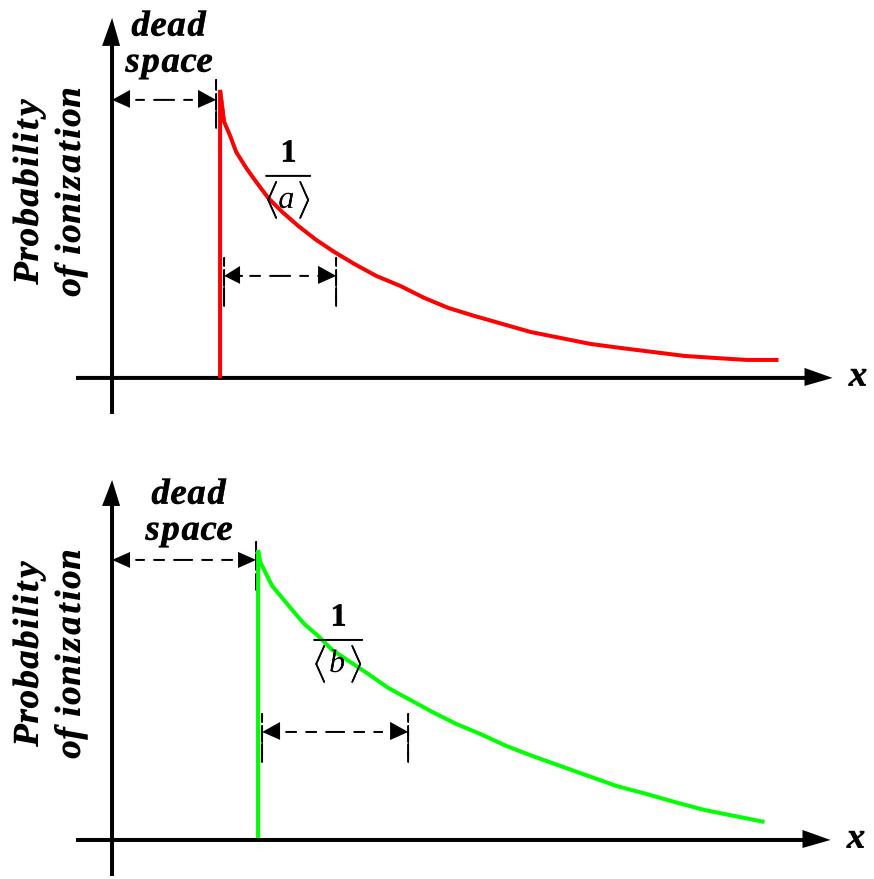
McIntyre Noise Model



- McIntyre's noise model assumes that a carrier's ionization probability is ***independent*** of distance ¾ probability density function (PDF) is exponential
- This assumption leads to the McIntyre expression for excess noise factor
- **Avalanche noise** depends on the b/a ratio

Dead Space Models

Probability density function of ionization



- More realistic picture of ionization probability shows **significant *dead space*** at high electric field
- Presence of dead space reduces ***CoV*** ¾ makes multiplication more deterministic ¾ less noisy
- A significant dead space reduces the importance of the *b/a* ratio & the carrier type initiating multiplication

Monte Carlo Estimation of F

$$M_{trial} = 1 + N_e + N_h$$

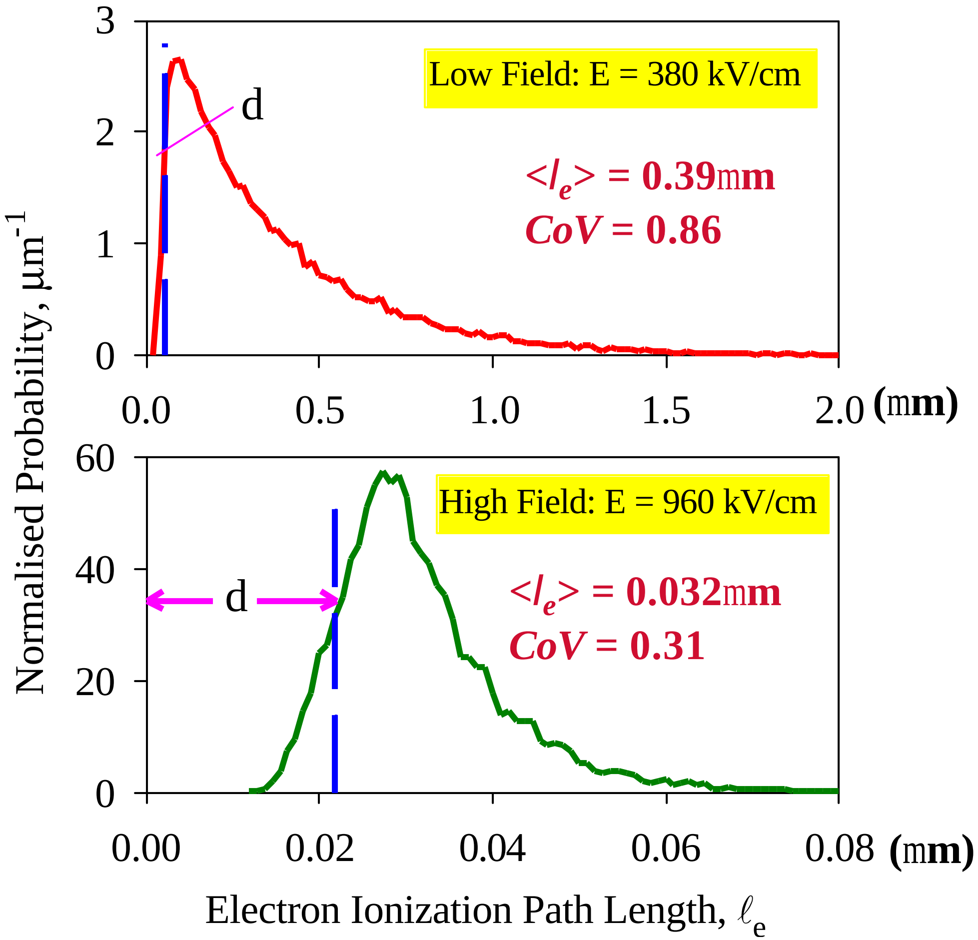
$$< M >= \frac{(M_1 + M_2 + \ldots + M_{N-1} + M_{N-2})}{N}$$

$$< M^2 >= \frac{(M_1{}^2 + M_2{}^2 + \ldots + M_{N-1}{}^2 + M_{N-2}{}^2)}{N}$$

Excess Noise Factor, $F = \dfrac{< M^2 >}{< M >^2}$

Probability distribution of electron ionization path lengths (<M> = 5)

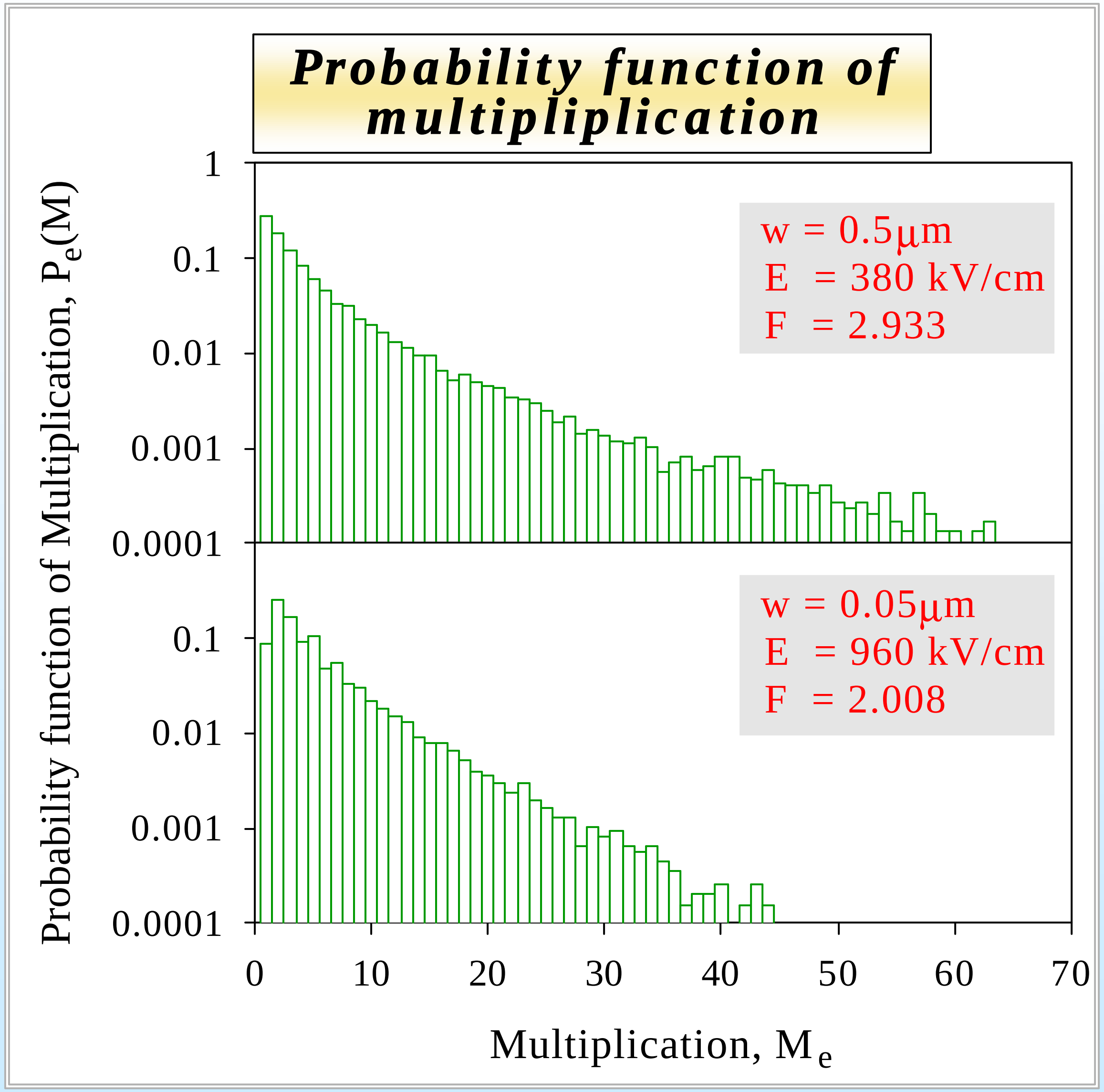
Probability density function of ionization



- **At *low fields* ⇨ relatively small dead space & low ionization probability**
- **At *high fields* ⇨ relatively large dead space & higher ionization probability ⇨ narrow ionization probability distribution.**

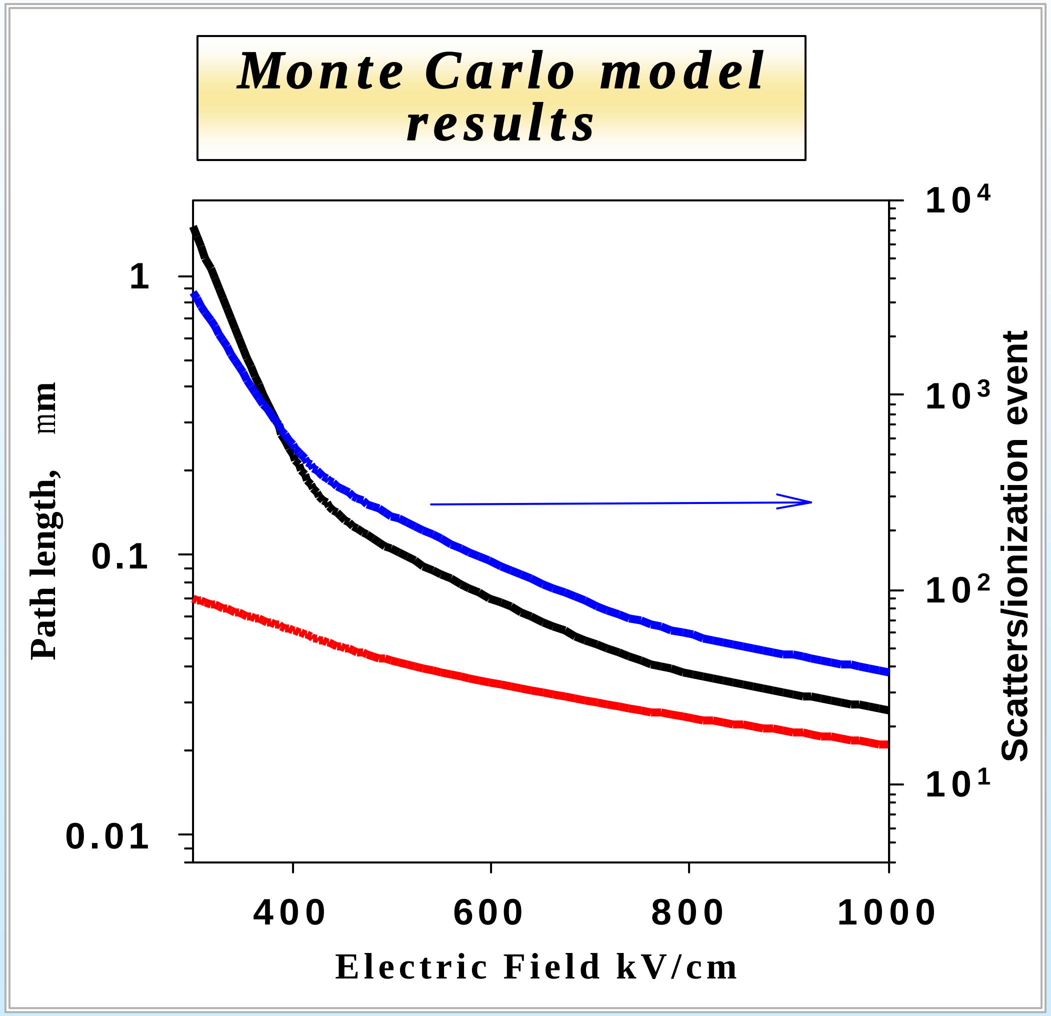
***CoV* = stand. dev. in l_e / $\langle l_e \rangle$**

Distribution of Multiplication for <M> = 5



- ***There are more high order multiplication events at lower electric fields, giving rise to more noise***

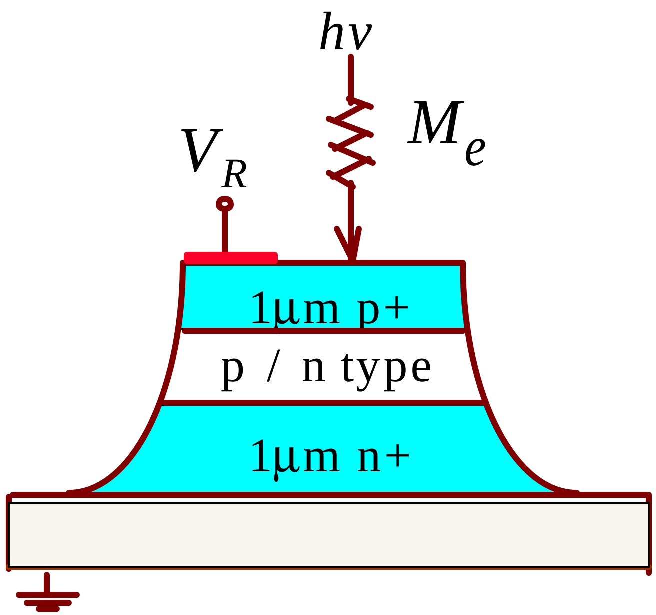
Typical path lengths as a function of electric field



- ***Scattering becomes less important as the electric field increases***
- ***Ionization tends towards ballistic ideal, i.e. like PMT***

Scatters per ionization event
Ballistic dead space
d **= 2.1eV/*qE***
Mean ionization path length <l_e>

Excess noise in p^+-n diodes



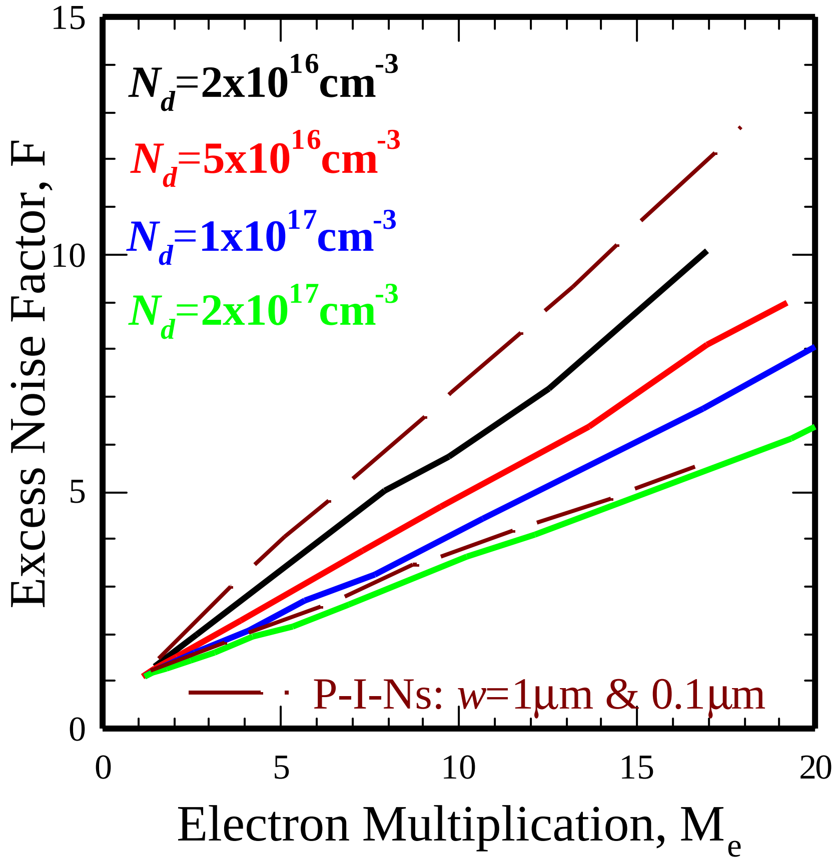
P or N doping varies from 2×10^{16} cm^{-3} to 3×10^{17} cm^{-3}.

- **Reducing *w* in p^+-i-n^+s reduces excess noise.**
- **How does increasing doping *i.e.* electric field gradient affect noise?**

Simulated excess noise in P^+N junctions

(... primary electrons are injected into the HIGH field)

Simulated excess noise results

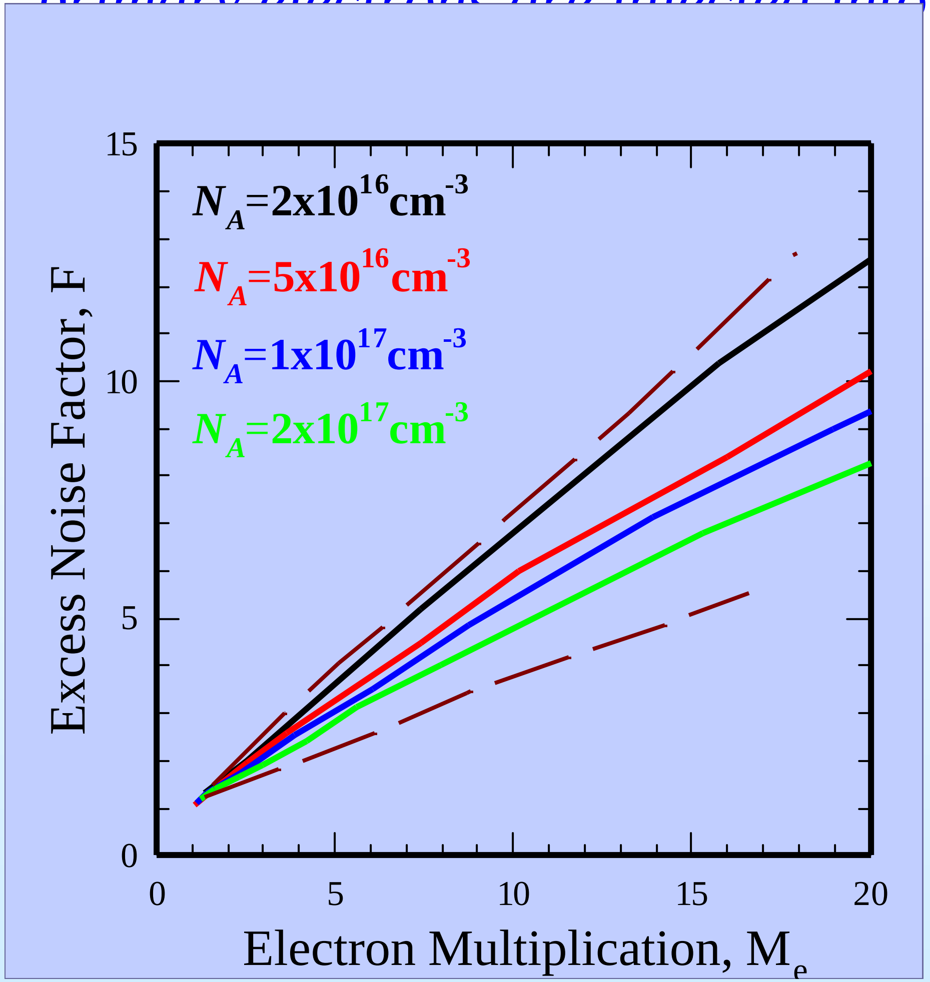


The excess noise is reduced by increasing the doping

For the same total depletion thickness, $F(P^+N) < F(P^+\text{-}I\text{-}N^+)$

Simulated excess noise in PN^+ junctions

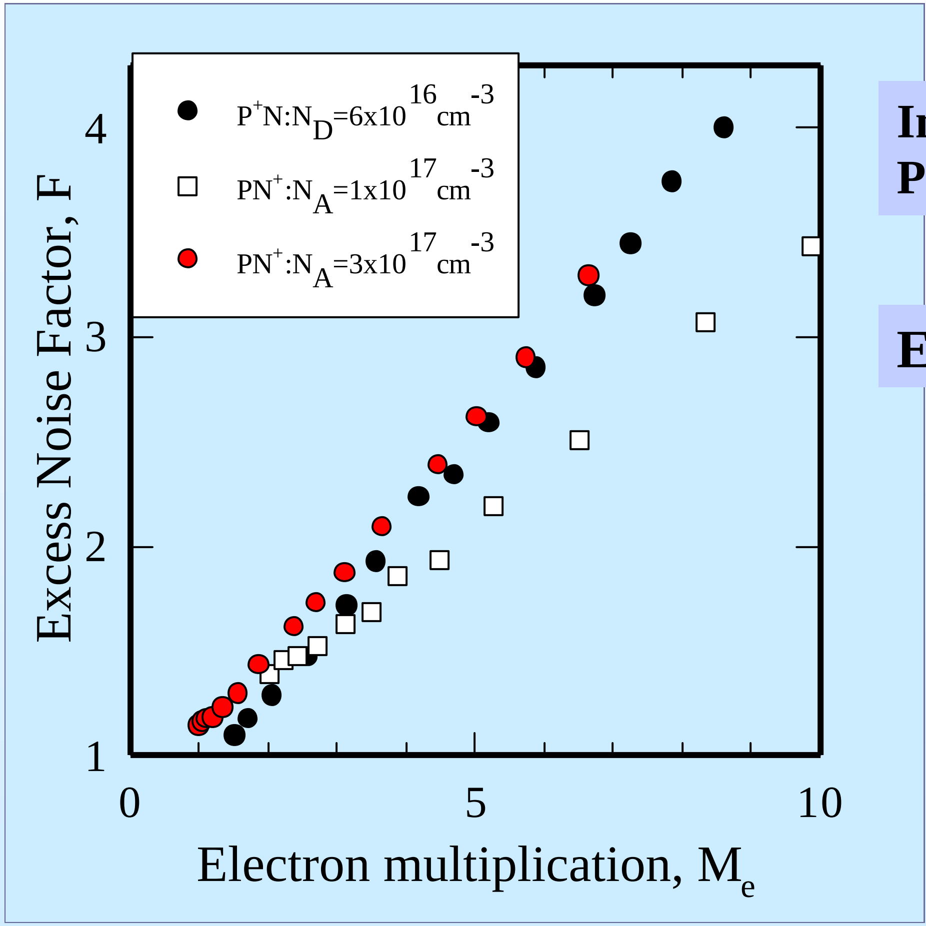
(.. primary electrons are injected into the LOW field)



The excess noise is again reduced by increased doping

For the same doping magnitude, $F(PN^+)$ is slightly greater than $F(P^+N)$

Experimental results with electron injection



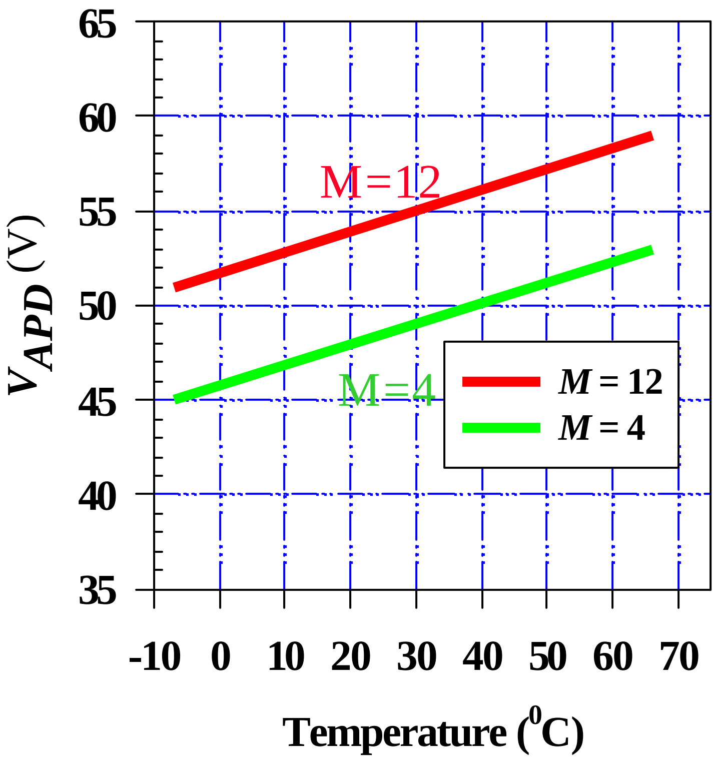
Increasing the doping in the PN^+ devices reduces noise

Experiment corroborates theory

Effect of temperature variation on APD performance

Temperature dependence of avalanche multiplication

Bias required for M = 4 & M = 12 at different temperatures

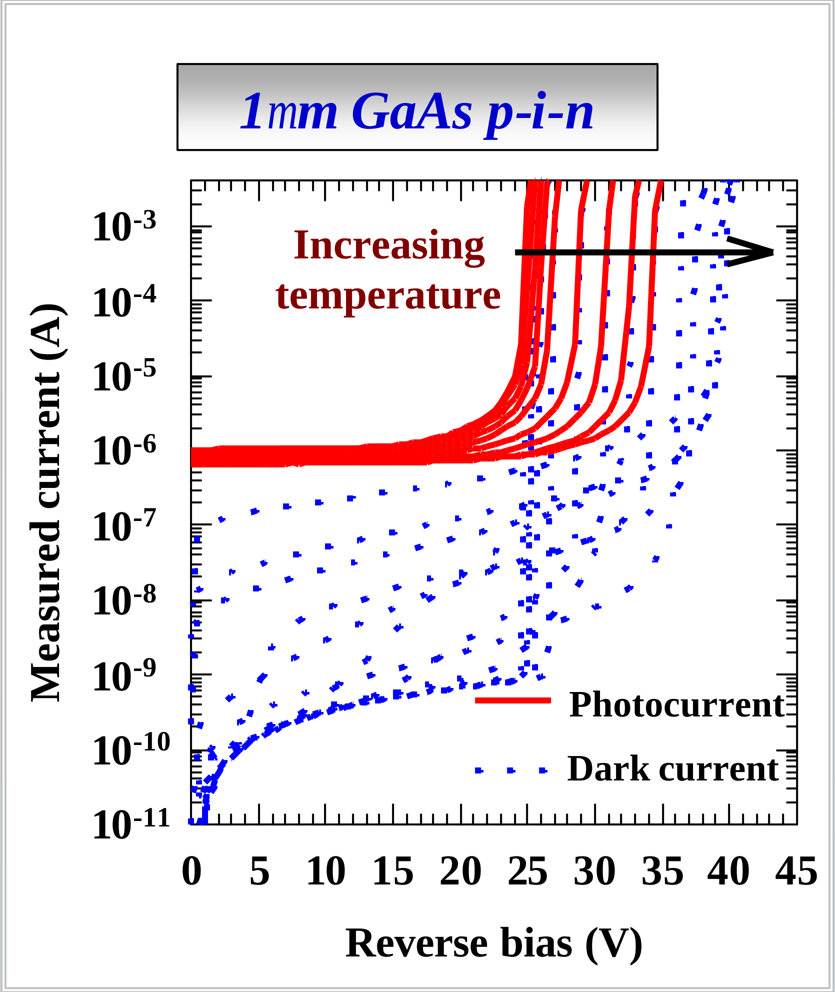


- ***APD multiplication is very temperature sensitive***

  Not a problem when input signal is large - BER increases when at the limit of sensitivity
- ***Breakdown variation is ~ 0.06-0.2V/°C***

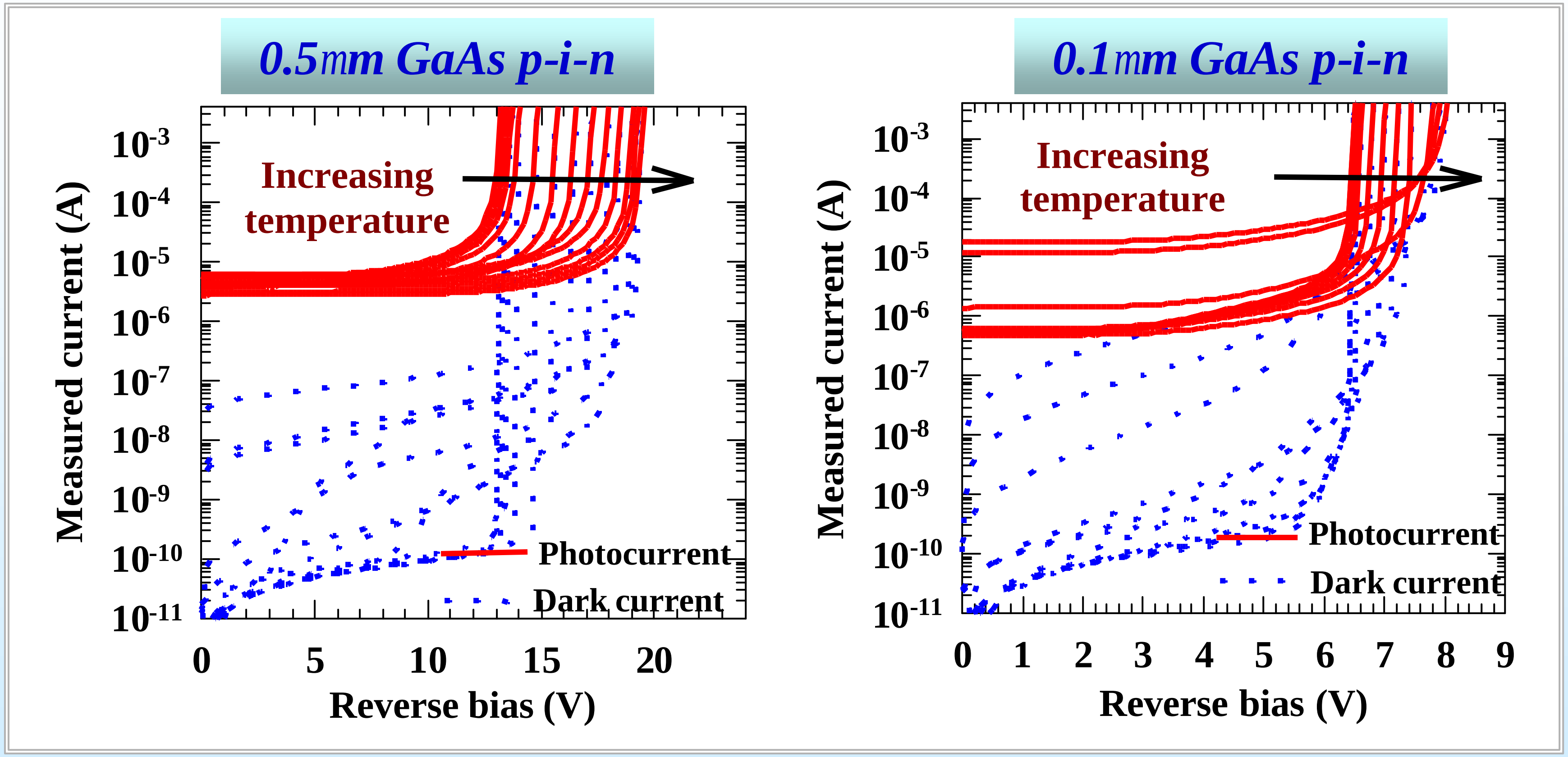
Active circuit required to vary bias to ensure constant multiplication

Temperature dependent I-V for 1mm GaAs



- ***Photocurrent, dark current and breakdown measured on different thickness GaAs p-i-n diodes, from 20K-500K***
- ***Sharp V_{bd} observed at all temperatures.***
- ***Dark currents increase with temperature***
- ***Avalanche multiplication reduces with increasing temperature***

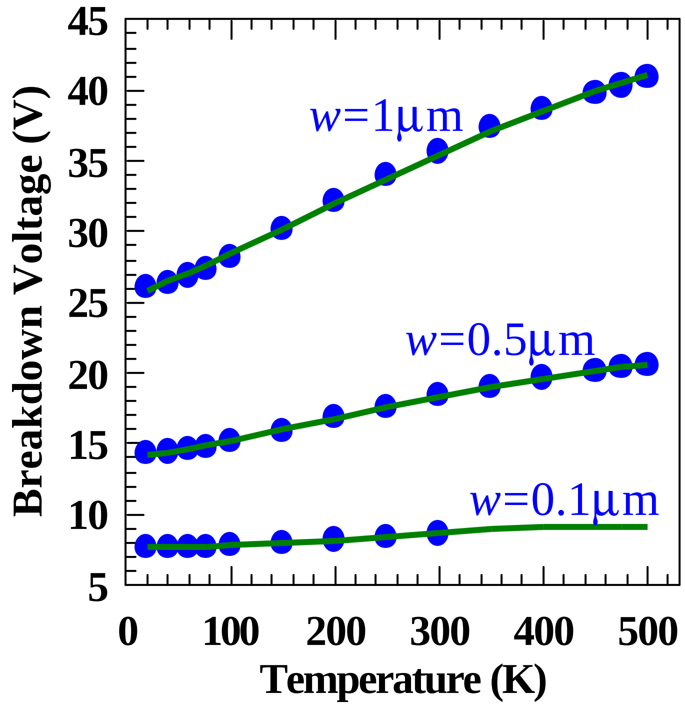
Temperature dependent I-V for 0.5μm & 0.1μm GaAs



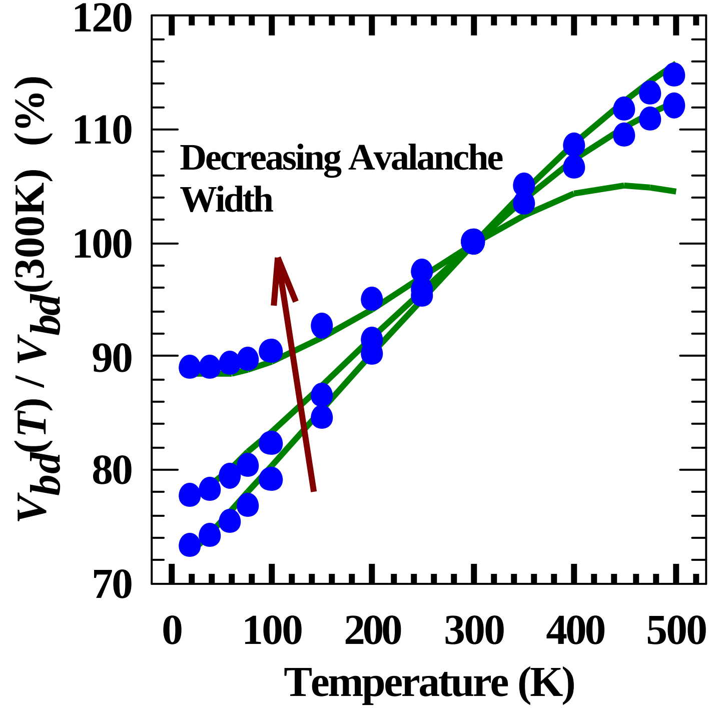
- *Similar behavior seen in thinner avalanche width structures*
- *Thinner devices are less affected by changes in temperature*

Change in V_{bd} with Temperature

w = 1.0 mm, 0.5mm & 0.1 mm



Percentage change in V_{bd}

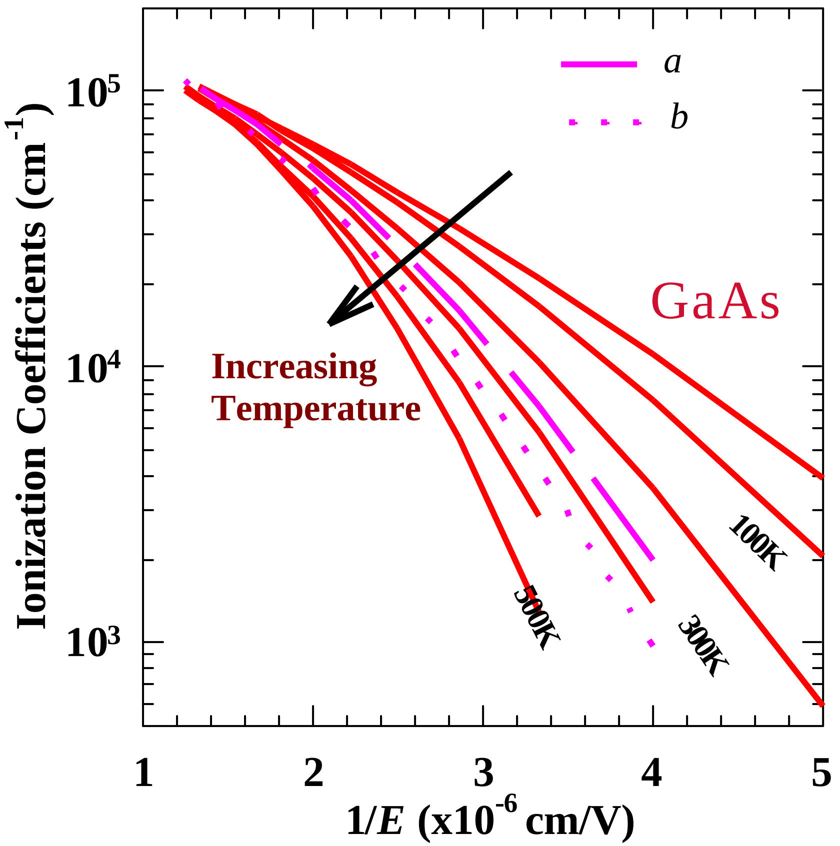


The breakdown change is more significant in thicker structures

Temperature coefficient decreases from 0.032V/°C to 0.004V/°C

Temperature dependent ionization coefficients

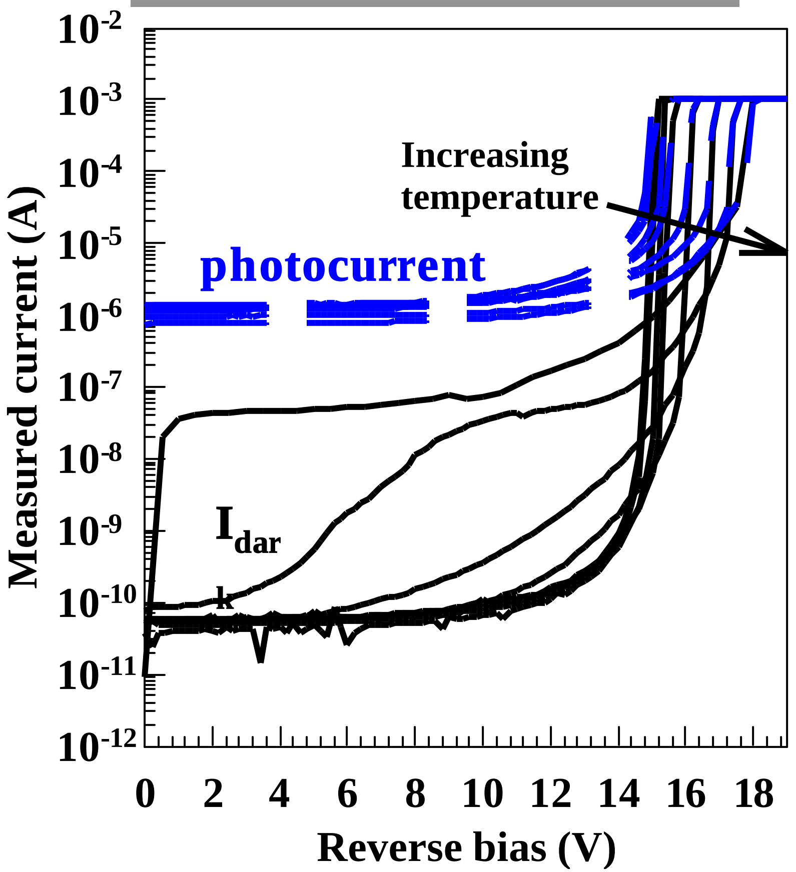
GaAs ionization coefficients



- ***Ionization coefficients derived from multiplication data***
- ***Ionization coefficients decrease with increasing temperature***
- ***The change is much larger at lower electric fields***
- ***Thinner avalanche widths operate at higher electric-fields***
- ***Phonon scattering relatively less important at higher electric fields***

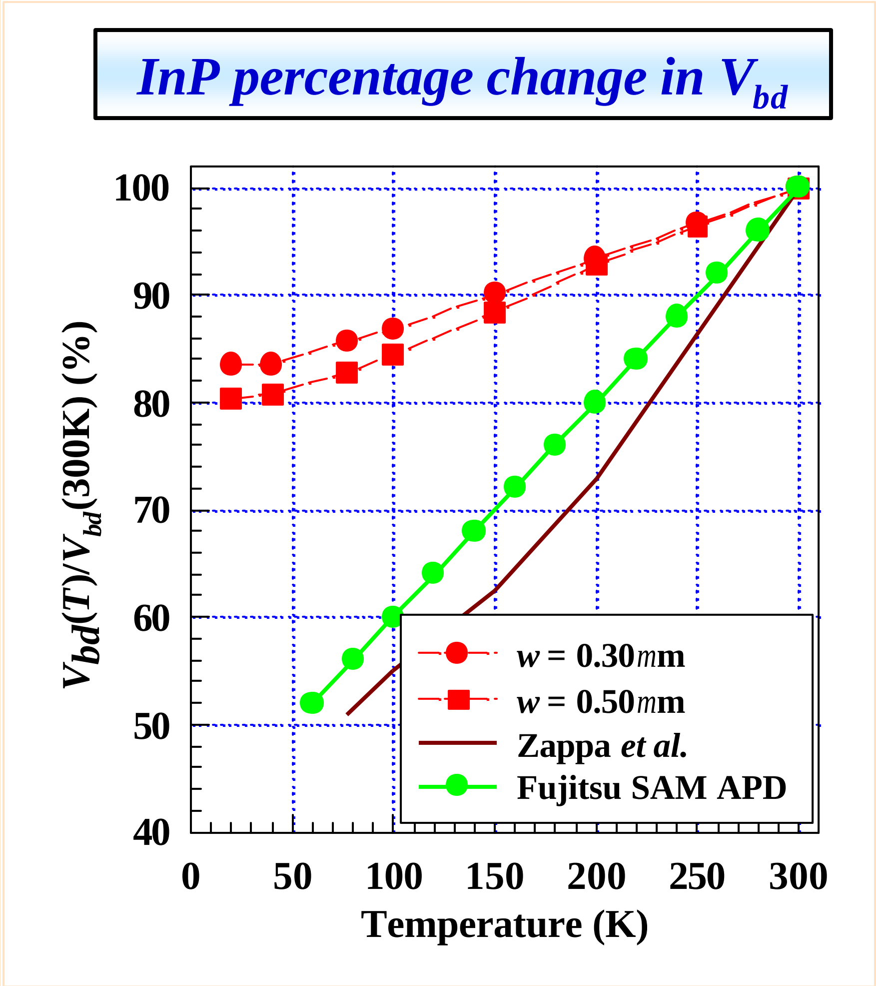
Temperature dependent I-V in thin InP

InP I-V characteristics



- ***Similar measurements on w = 0.3mm InP p-i-n from 20K-300K***
- ***Low dark current and***
- ***Sharp breakdown observed***
- ***V_{bd} decreases as temperature decreases***
- ***Similar results observed in structure with w = 0.5mm.***

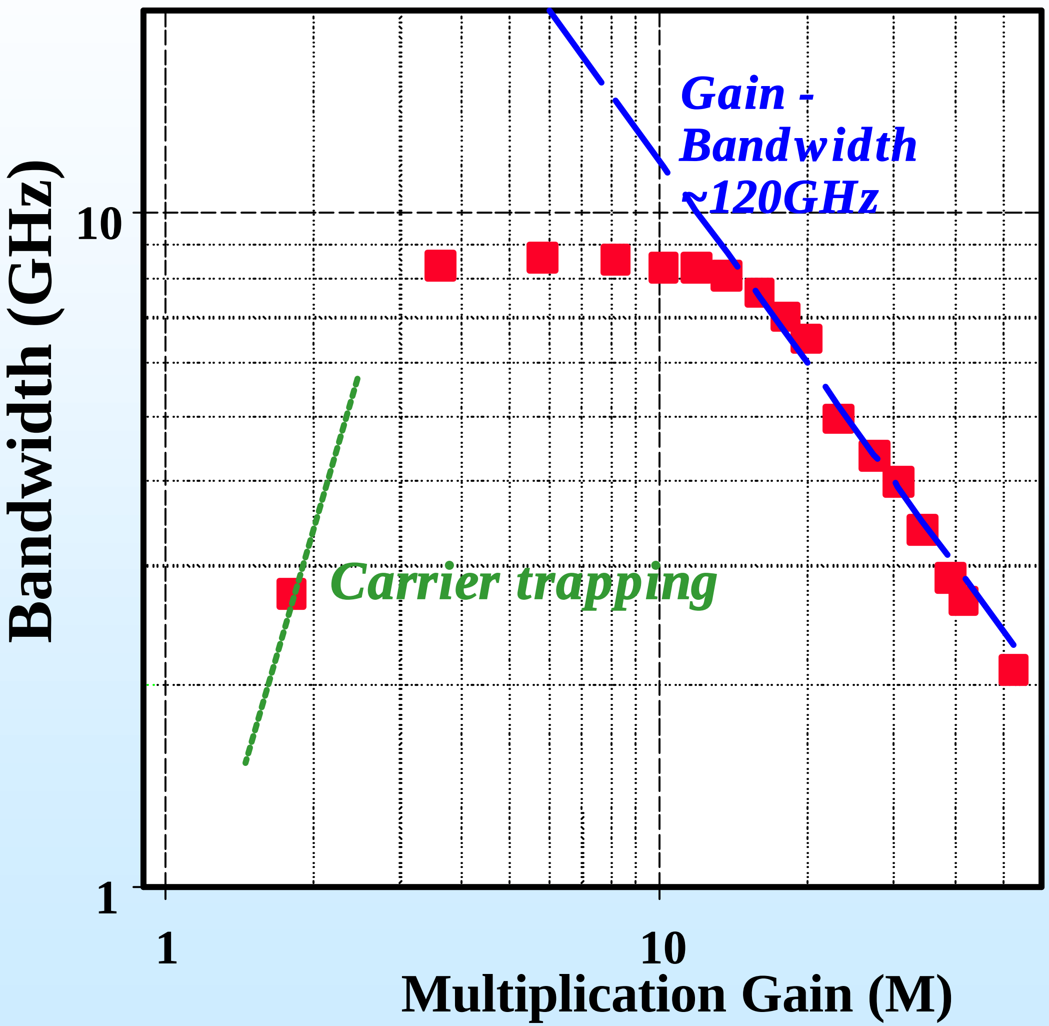
InP temperature coefficient of V_{bd}



- ***Lower temperature coefficient of breakdown voltage,*** h_o ***as w decreases.***
- ***Zappa et al (IPRM'96):*** h_o ***~ 0.225V/°C***
- ***Fujitsu SAM-APD:*** h_o ***~ 0.09 - 0.15V/°C***
- ***w = 0.3mm:*** h_o ***~ 0.012V/°C***
- ***w = 0.5mm:*** h_o ***~ 0.02V/°C***

Effect of thin avalanching widths on APD speed

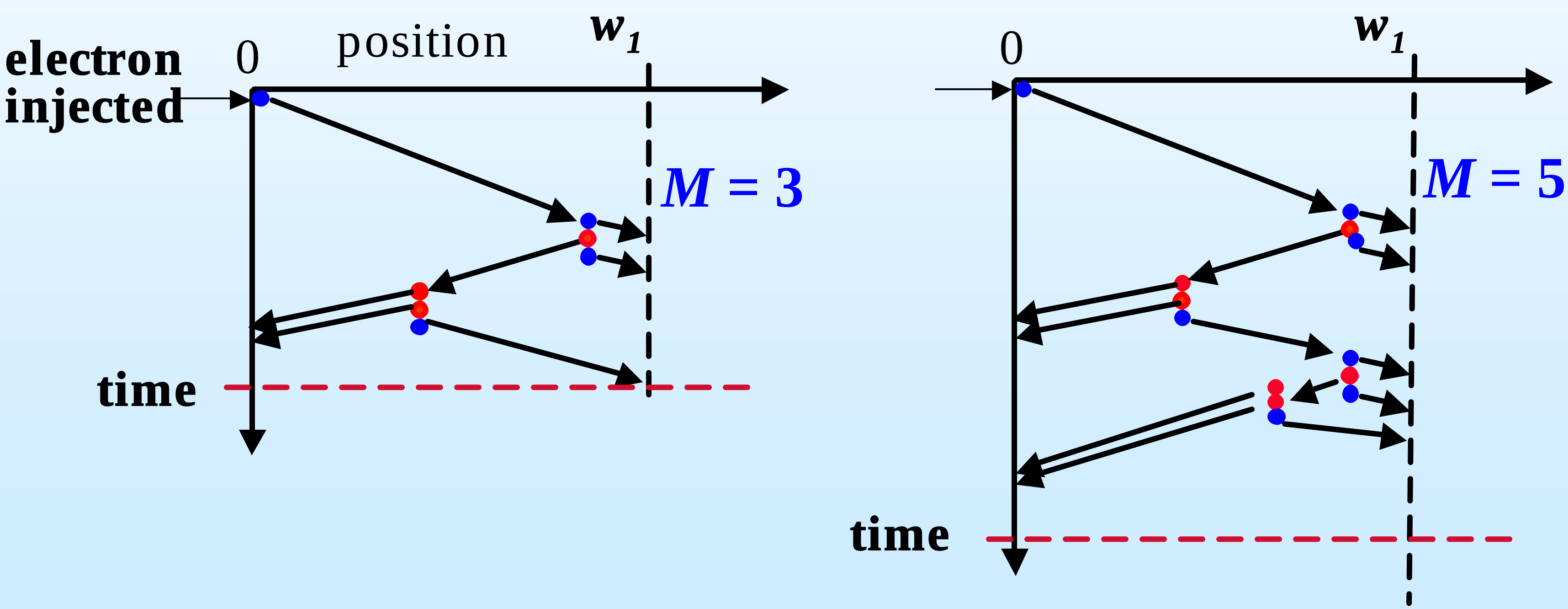
Gain-bandwidth Characteristics



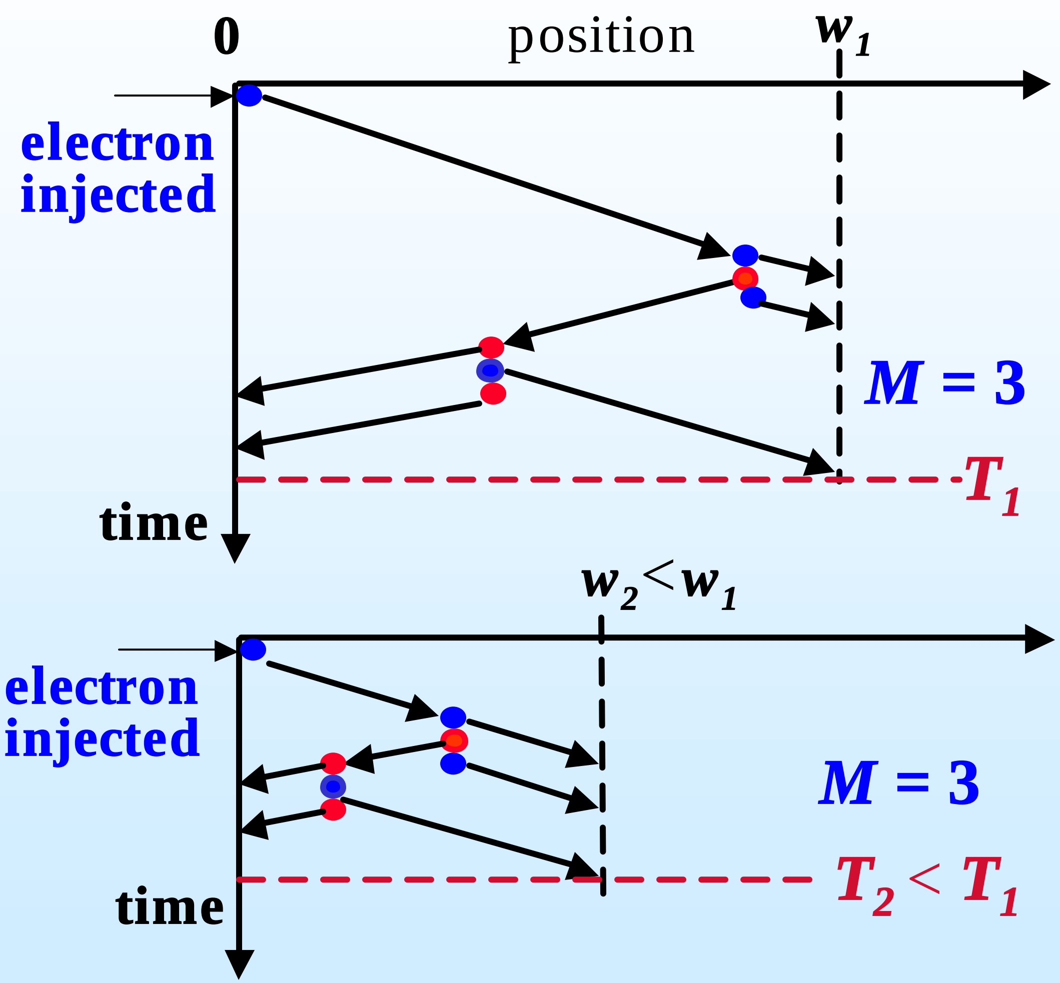
- ***Bandwidth decreases at low multiplication - carrier trapping***
- ***Bandwidth decreases at high multiplication - multiple transits***

APD speed limitations-multiplication build-up time

- ***APD is slow c.f. p-i-n diodes due to multiple transits required for high gains***
- ***Difficult to achieve 10 Gb/s operation with thick avalanching structures***



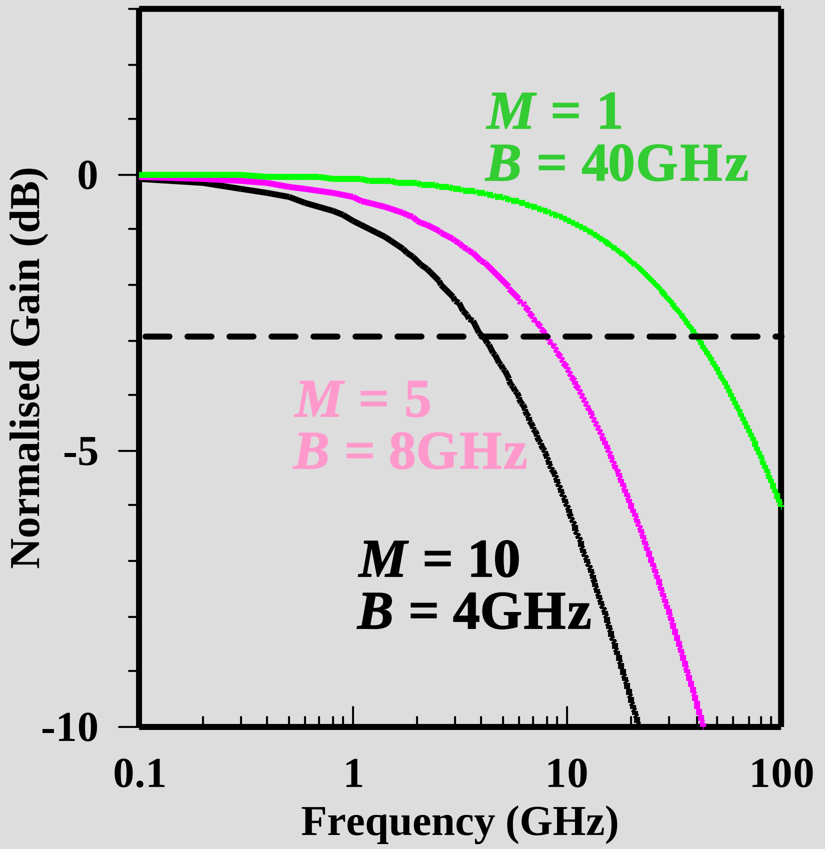
Thin avalanche region multiplication build-up time



Decreasing w results in shorter transit times - higher speed

APD limitations - frequency response

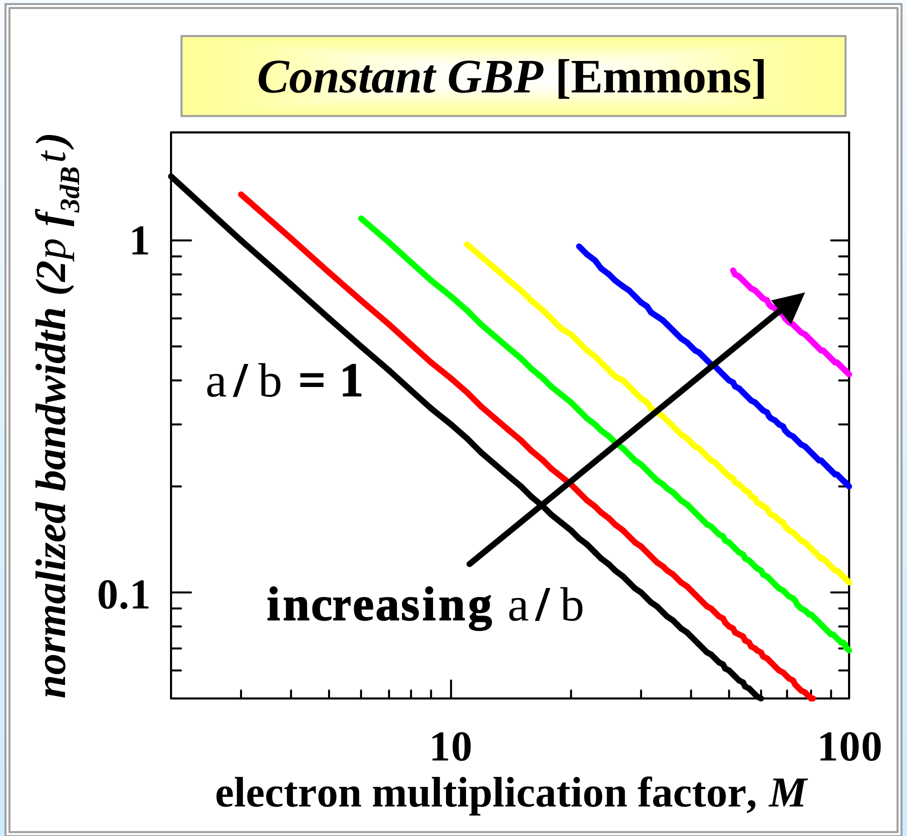
Frequency response of APDs for fixed reverse bias



- *APD frequency response approximates a 1st order system*
- *Figure of merit - Gain bandwidth product (GBP)*
- *Motivation of thin avalanche regions < 1μm to increase GBP*

Multiplication-limited bandwidth

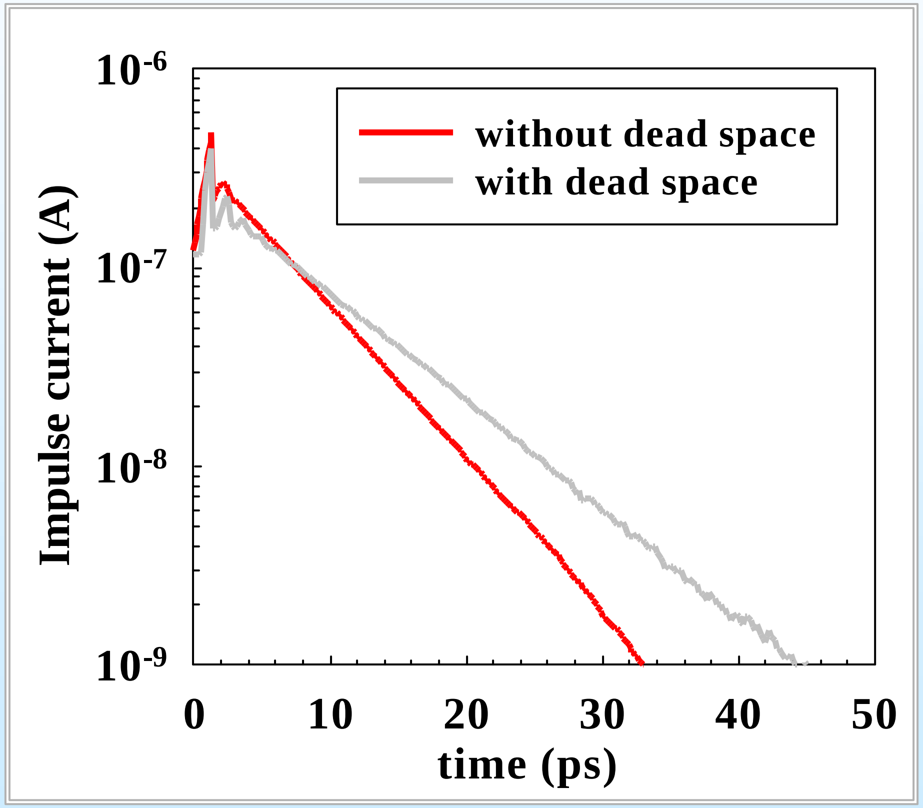
- ***Factors affecting APD speed: Carrier transit time, RC time constant, carrier diffusion and multiplication buildup time (f_{3dB})***



- *Conventional (Emmons') model* [Emmons, 1967]
  - *Negligible dead space* ⇨ $d = 0$
  - *Constant carrier speed* ⇨ $v = v_{sat}$ *(saturated drift velocity)*
  - *Constant gain-bandwidth product,GBP*
  - *GBP scales with* t *, carrier transit time*

Effect of dead space on speed

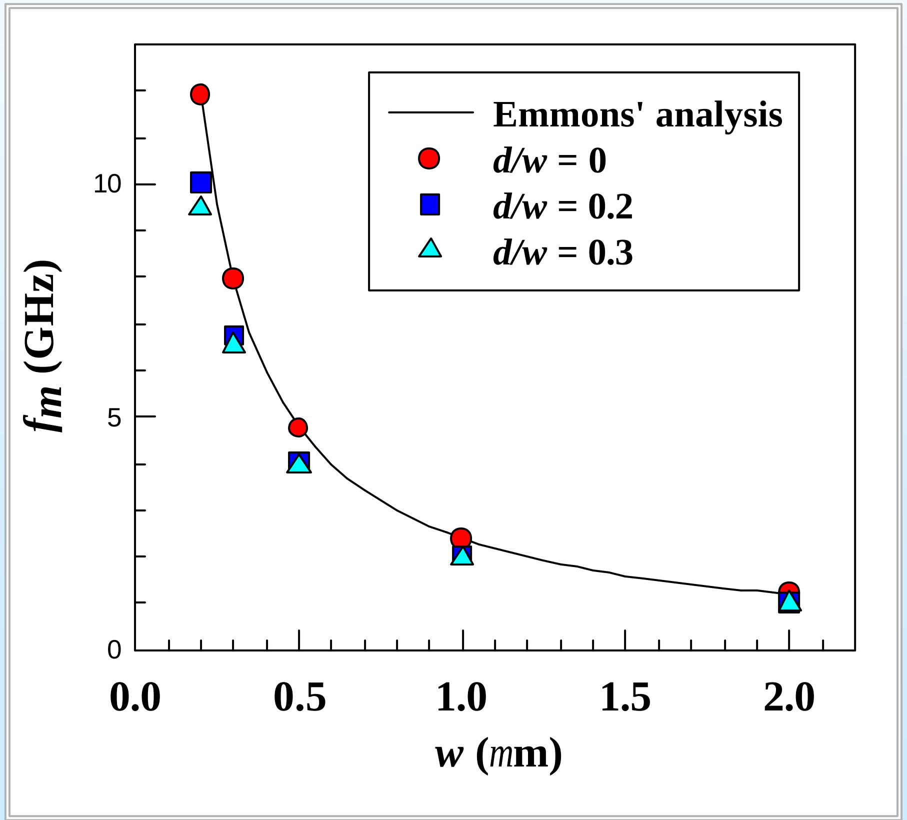
- ***Comparison of $d = 0$ cf. non-local model with $d \neq 0$***



- ***$v = v_{sat}$***
- ***Avalanching region width of $w = 0.1\mu m$***
- ***$M = 12.5$***
- ***d ⇧, avalanche current impulse response decays more slowly ⇨ lower f_{3dB} [Hayat and Saleh, 1992]***

Effects of dead space

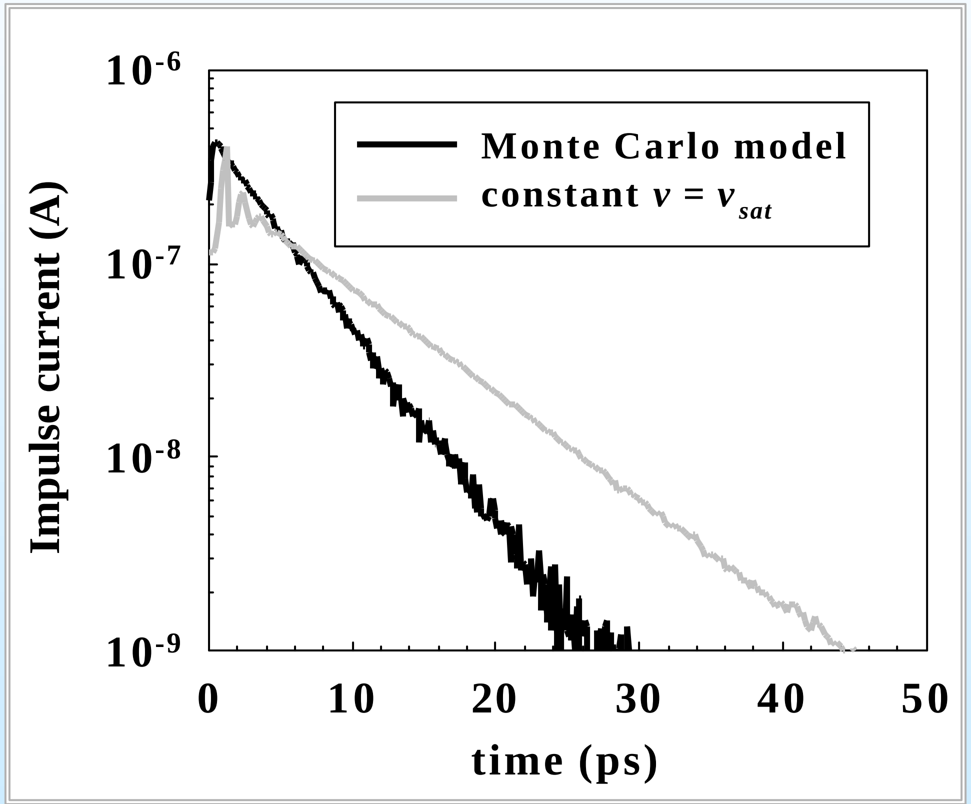
- f_m of APDs with avalanche width of w, $\alpha = \beta$ and <M> = 20
- Compare d/w = 0, 0.2 and 0.3



- Obtain f_m by Fourier transforming the current impulse response
- f_m obtained agrees with Emmons' prediction for d/w = 0
- As d/w increases, f_m falls below the predicted values
- d/w is larger in thin APDs ⇨ absolute decrease in f_m is larger in thin APDs

Carrier speed assumptions

- ***Monte Carlo model* cf. *constant $v = v_{sat}$ model***
- ***Same dead space, d***

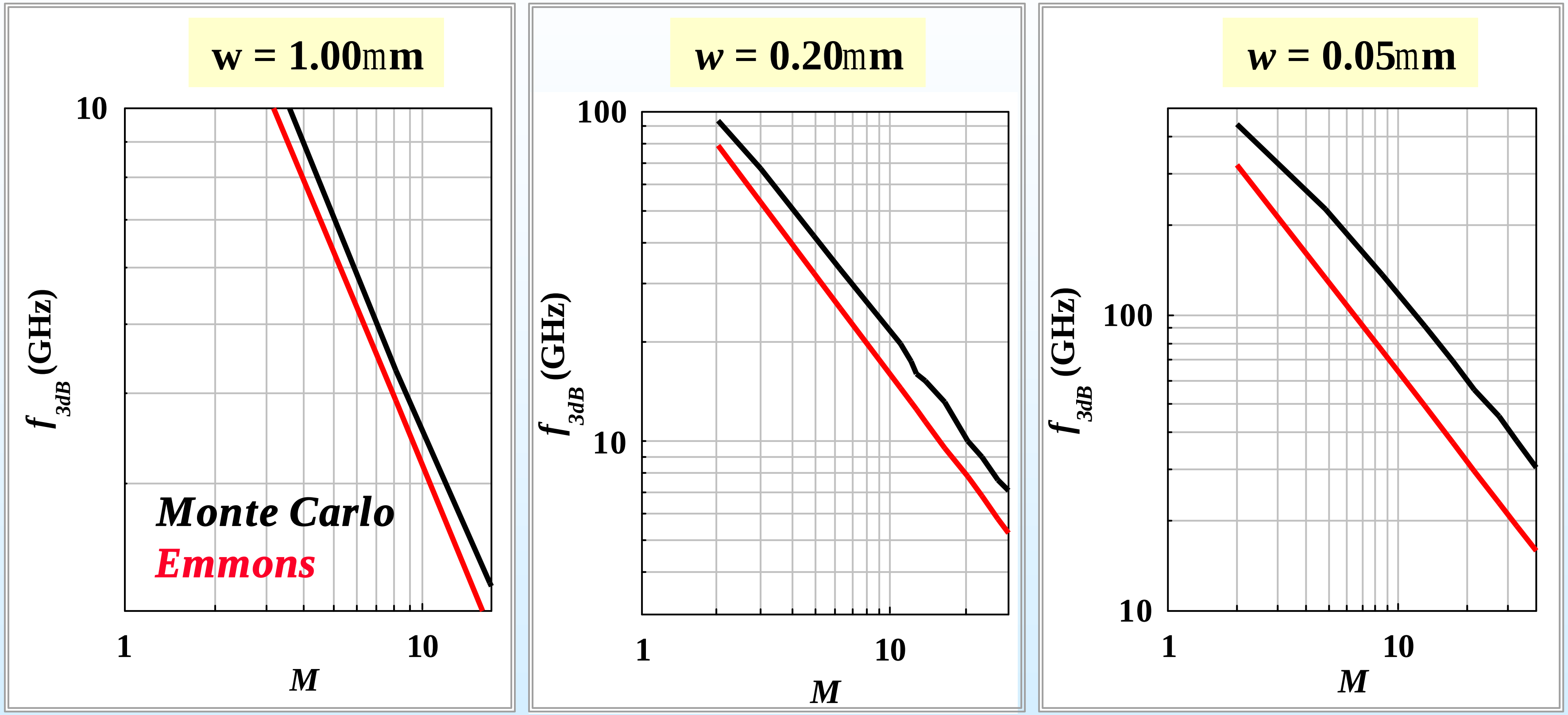


- ***$w = 0.1\mu m$, $M = 12.5$***
- ***Enhanced speed in MC model leads to faster decay of current impulse response ⇨ higher f_{3dB}***

- ***Dead space and enhanced speed effects compete!***

[Hambleton et al, 2002]

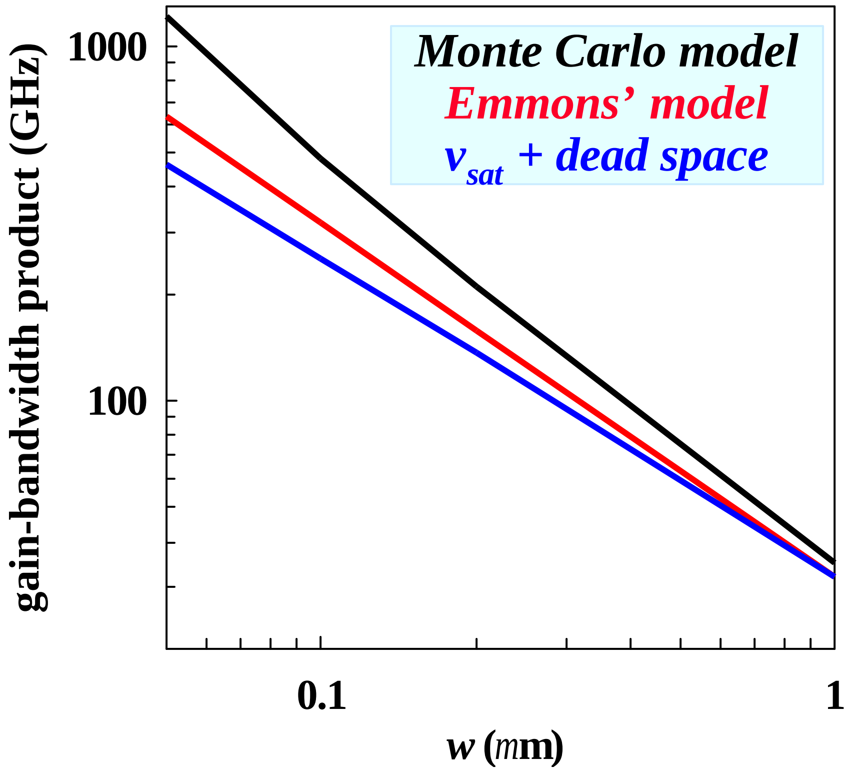
Simulation result comparisons



- ***Constant GBP***
- ***f_{3dB} (Monte Carlo) > f_{3dB} (Emmons) for all w and all M***
- ***Enhanced carrier speed dominates dead space***

GBP comparison

GBP (Monte Carlo) > GBP (Emmons) > GBP (v_{sat} + dead space)



- Monte Carlo ↑ more rapidly as w ↓ than Emmons and (v_{sat} + dead space)
- GBP enhancement ↑ as w ↓
- Worst case is using (v_{sat} + dead space)

Published experimental f_{3dB}

- Lenox et al. (PTL 1999) measured f_{3dB} of InAlAs RCE APDs
  - w = 400 nm GBW = 130 GHz
  - w = 200 nm GBW = 290 GHz
- $GBP_{200nm} > 2 \times GBP_{400nm}$

- Emmons' model predicts $GBP_{200nm} = 2 \times GBP_{400nm}$
- But larger d/w in w = 200nm device slows frequency response
- Suggests $v_{200nm} > v_{400nm}$

Conclusions

- The *excess noise* decreases as the avalanche width decreases below 1*m*m, in disagreement with the theory of McIntyre
- The low noise results from a more deterministic impact ionization process at high fields as *dead space* becomes more important
- The carrier type initiating the multiplication becomes unimportant at high fields
- Thin avalanching regions should be less temperature sensitive
- Thin avalanching regions should be capable of high speed operation
- 40 Gb/s APDs highly probable

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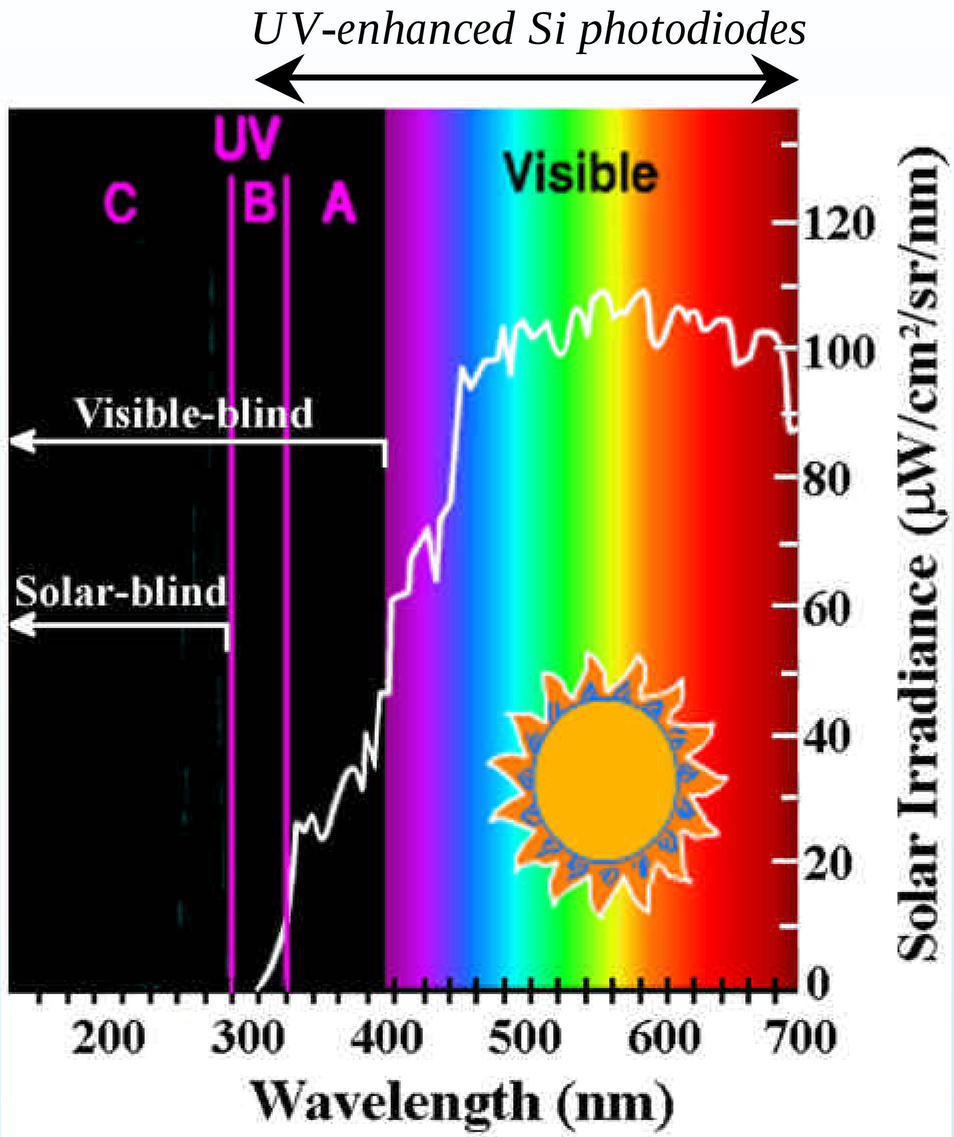
B. Jacob, P.J. Hambleton, C.N. Harrison, M. Yee,

D.S. Ong, C.K. Chia, R. Ghin, K.F. Li, S.A. Plimmer, G.M. Dunn

IEEE LEOS, EPSRC, DERA, EU

UV Detection



- **Applications requiring UV detection**
  - ***Atmospheric UV remote sensing***
  - ***UV astronomy***
  - ***Combustion control***
  - ***Detection of fire, corona discharge on HV lines***
  - ***Aircraft & missile detection***

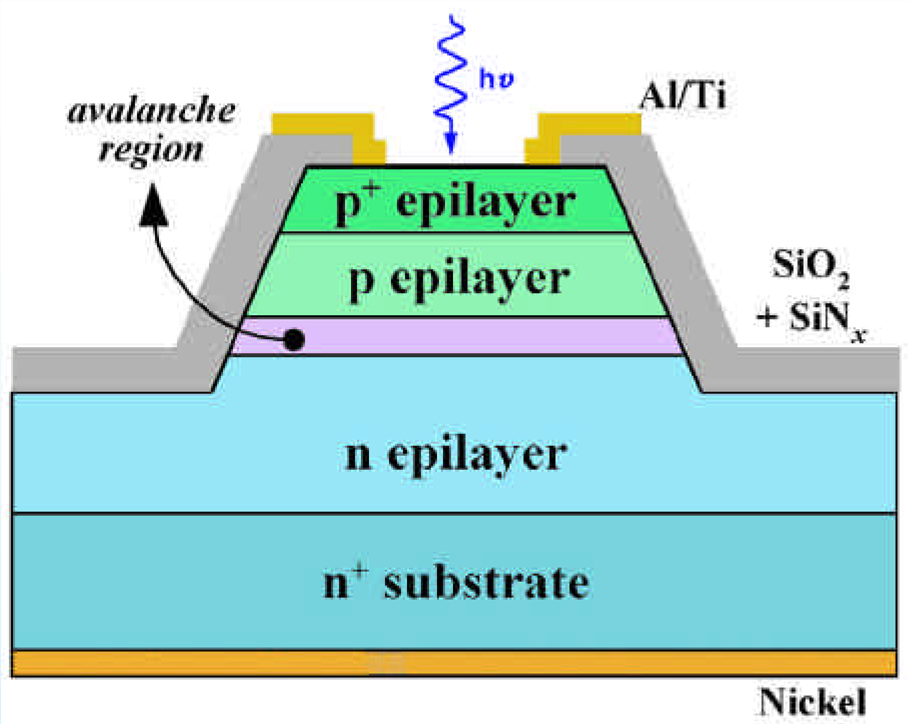
Motivation

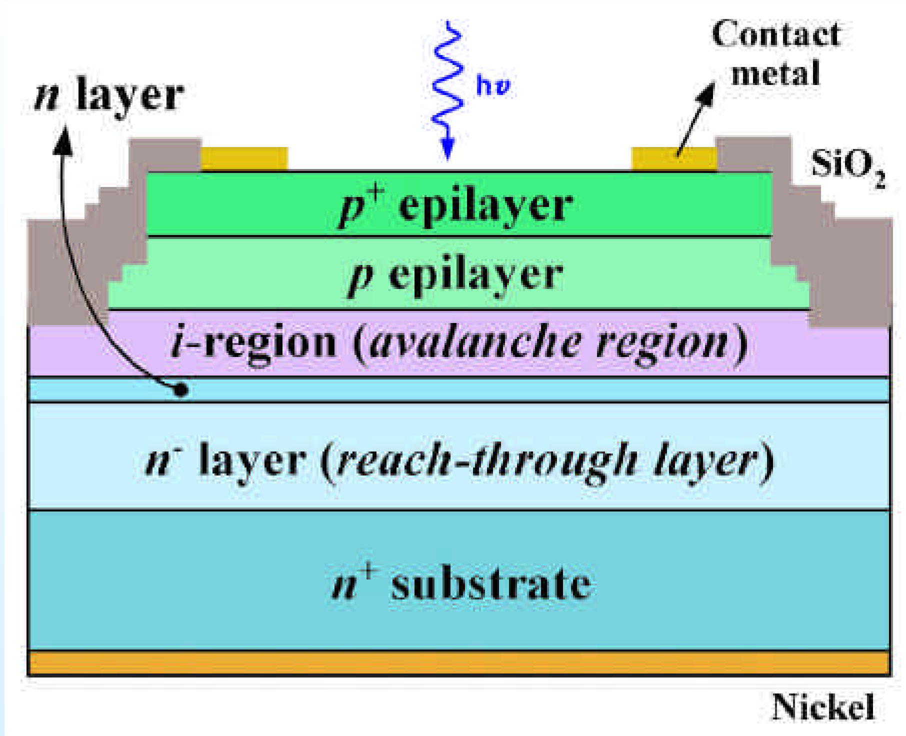
Why SiC for UV APDs?

- **Wide bandgap (3.25eV for 4H-SiC)**
  - ⇒ ***excellent for UV detection***
  - ⇒ ***very low dark current***
  - ⇒ ***high temperature operation***

- **Large** b/a **ratio in 4H-SiC**
  - ⇒ ***desirable for thick APD structures***
  - ⇒ ***performance in thin structures unknown***

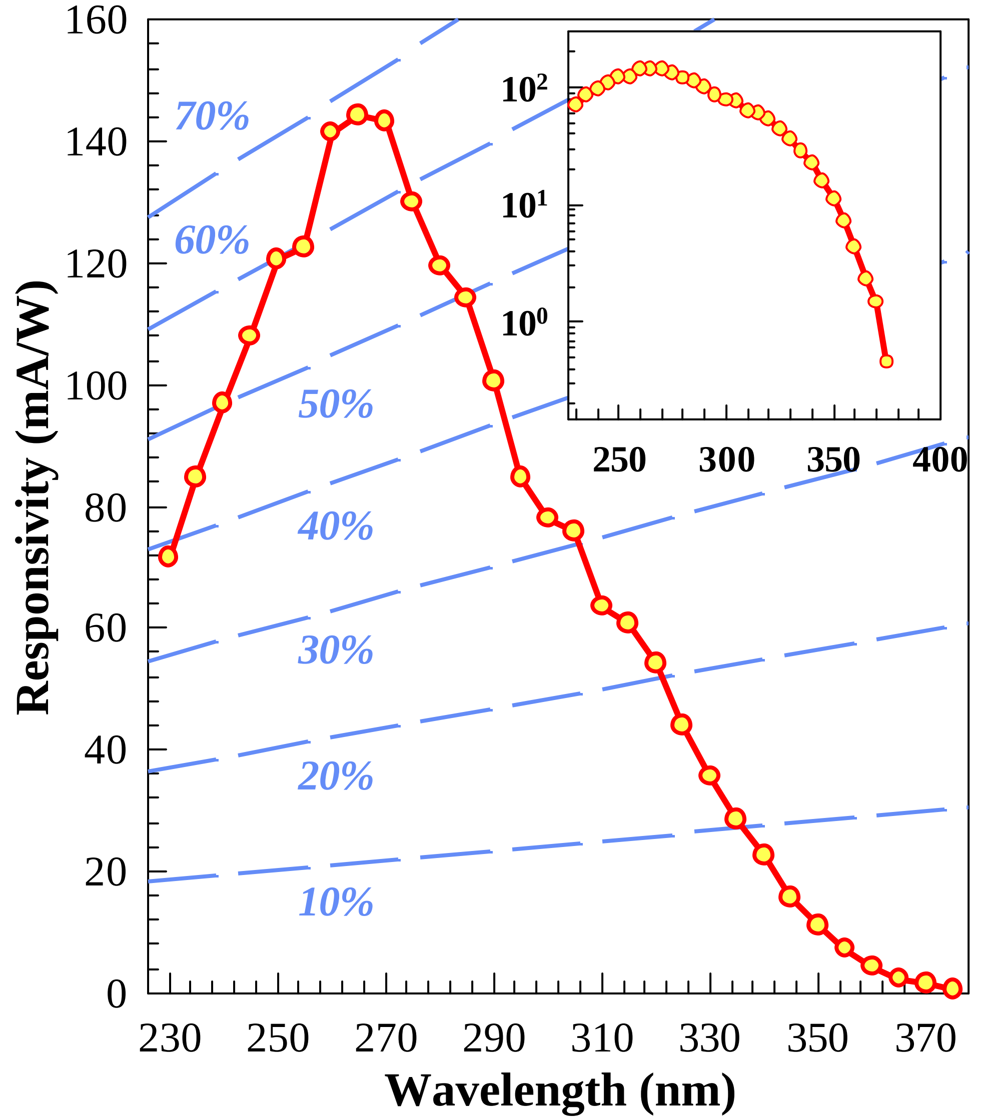
4H-SiC Device Structures





- 2° +ve bevel edge & multistep junction extension termination
- Square mesas with areas : 50 ´ 50 ~ 210 ´ 210 mm^2
- Passivated with SiO_2 & SiN_x
- Al/Ti top contact with optical access

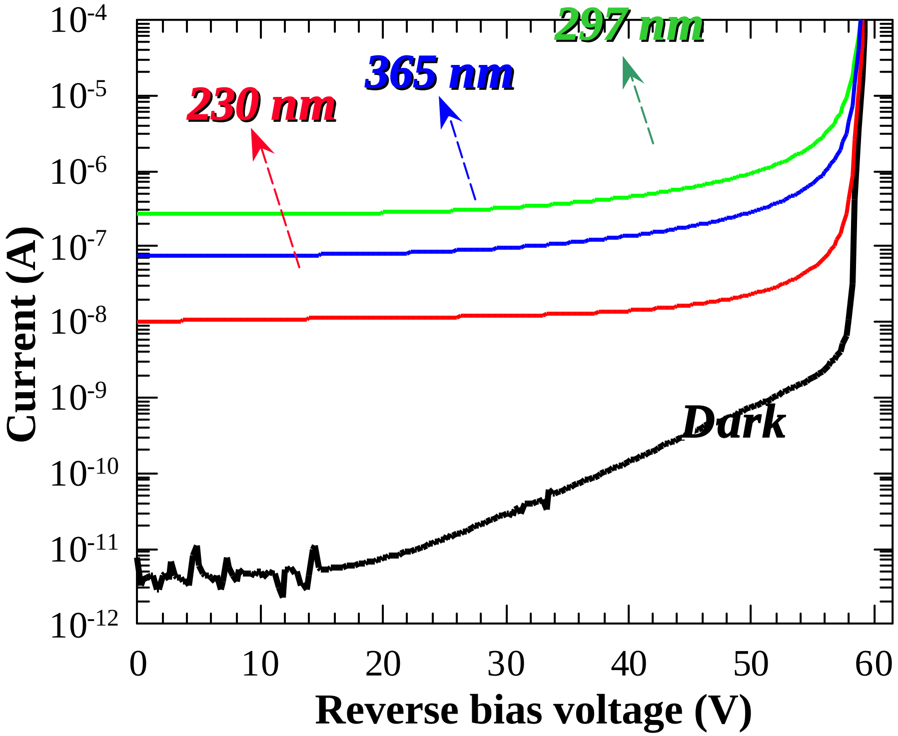
Responsivity at Unity Gain, Beveled APDs



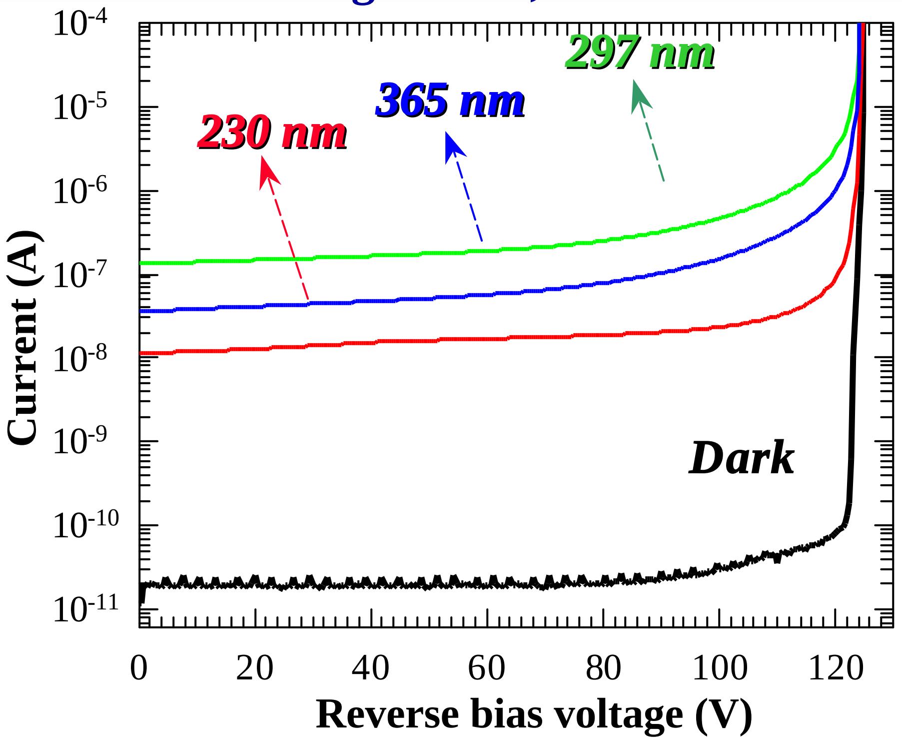
- **Similar to typical 6H-SiC photodiodes**
- **Responsivity cutoff at ~380 nm Þ *visible-blind***
- **Peak responsivity of 144 mA/W at 265 nm Þ *quantum efficiency of ~ 67%***

Reverse IV Characteristics

Beveled APDs, 160´160mm^2



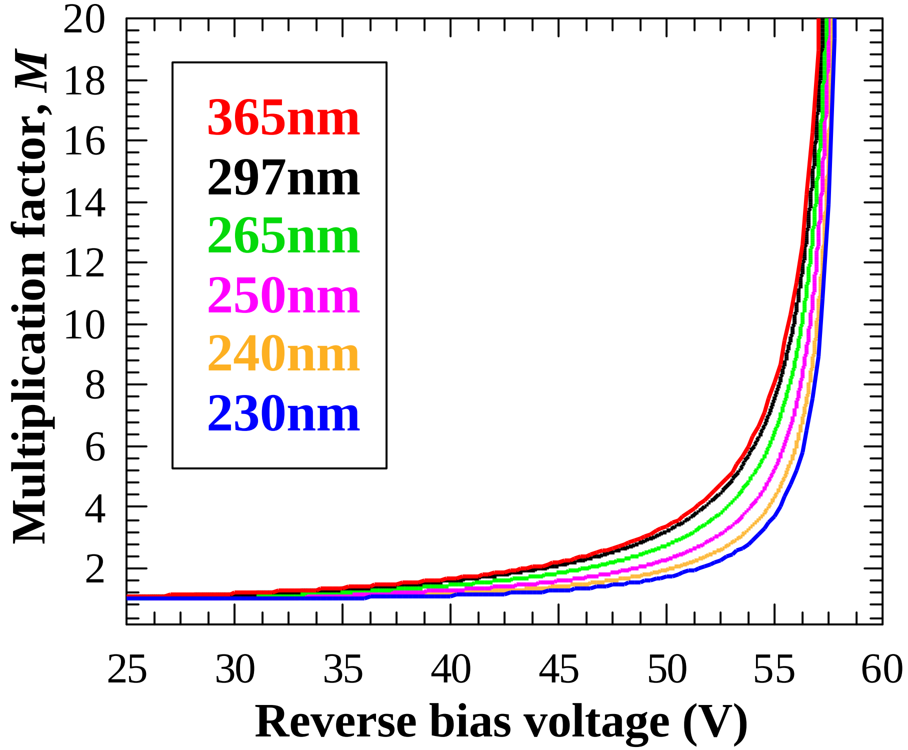
Reach-Through APDs, 150´150mm^2



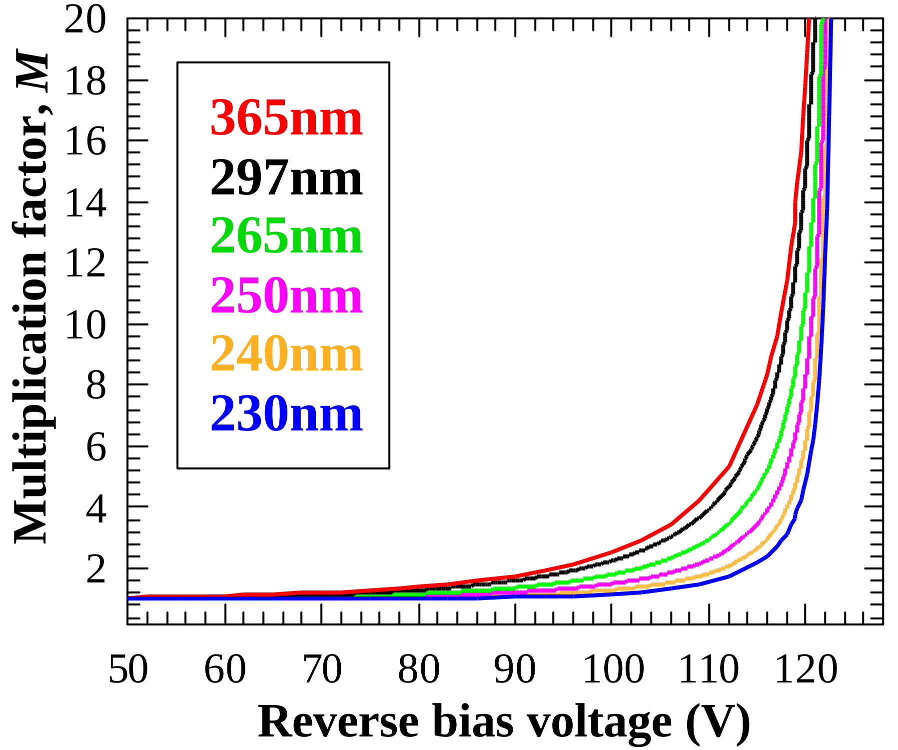
- **Avalanche breakdown is sharp & well-defined at V_{bd} = 58.5V & 124.0V**
- **Carriers injected with 230 ~ 365 nm light to initiate multiplication**
- **I_{ph} is 1 ~ 3 orders of magnitude > I_{dark}**
- **AC measurements corroborate DC results**

Multiplication Characteristics

Beveled APDs



Reach-Through APDs

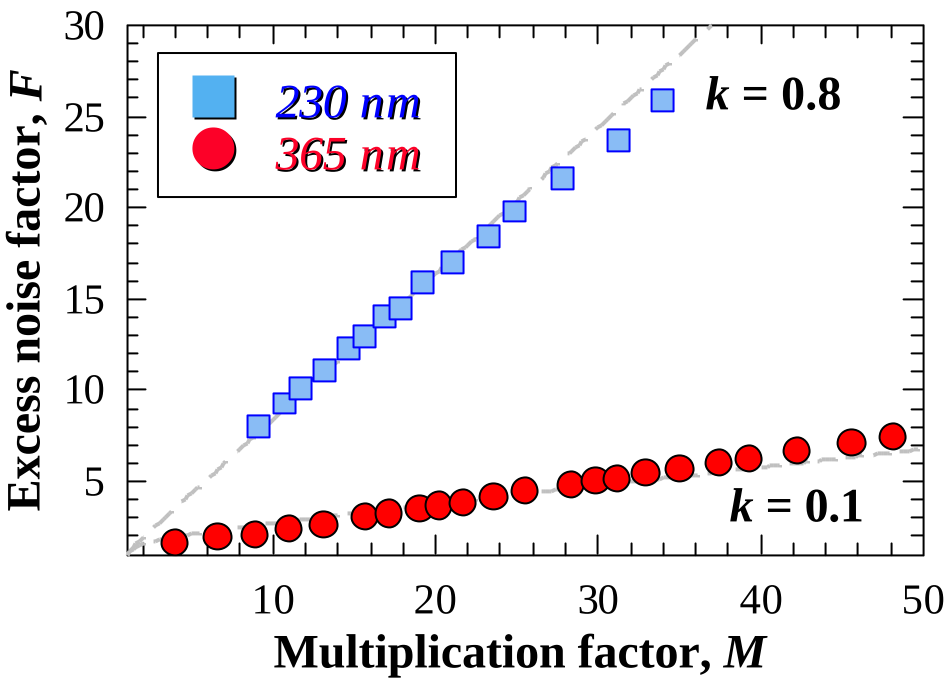


- ***M*** **of > 200 measured**
- ***M*** **at various l more disparate for thicker APD structure**
- **Smaller *M* from shorter l**

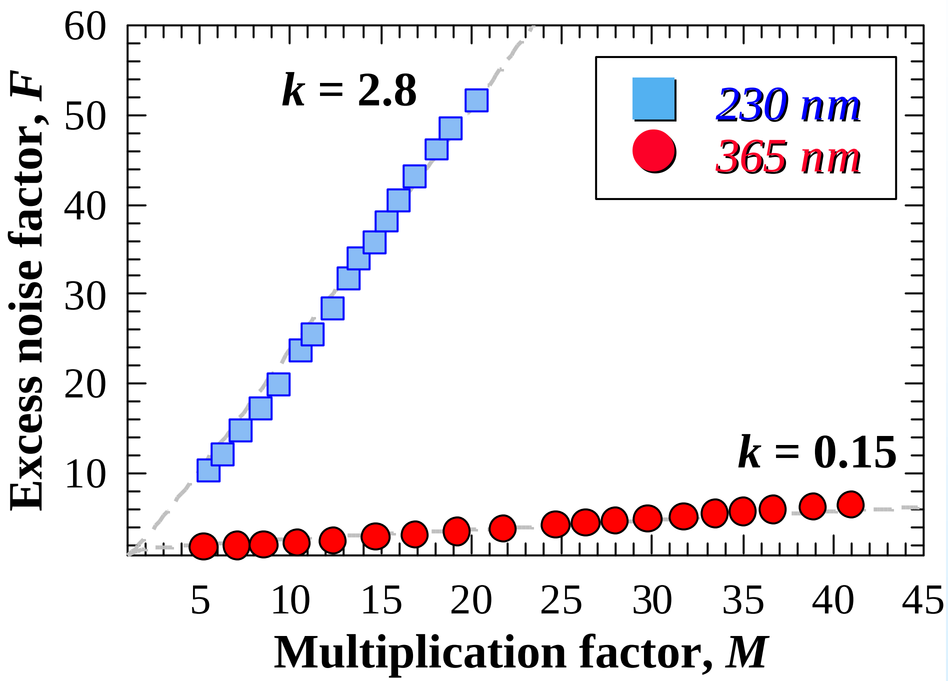
  Þ $M_h > M_e$ Þ b > a

Excess Avalanche Noise Characteristics

Beveled APDs

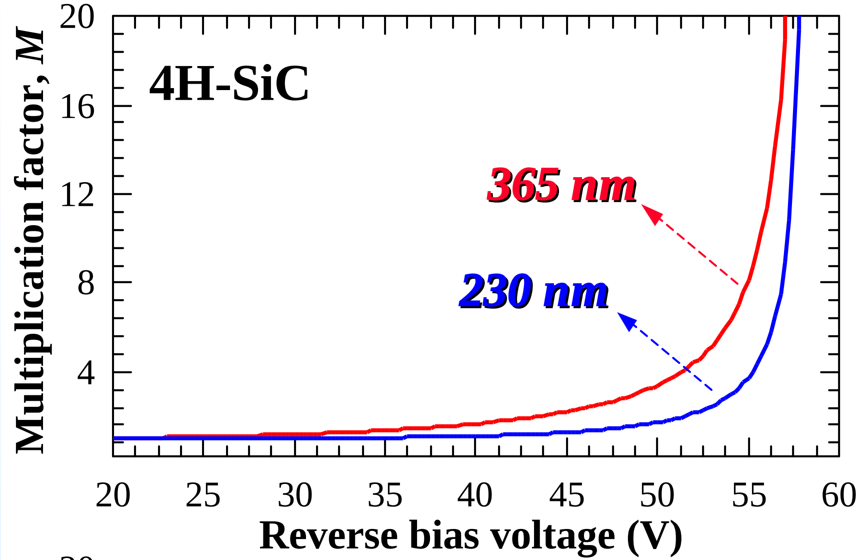


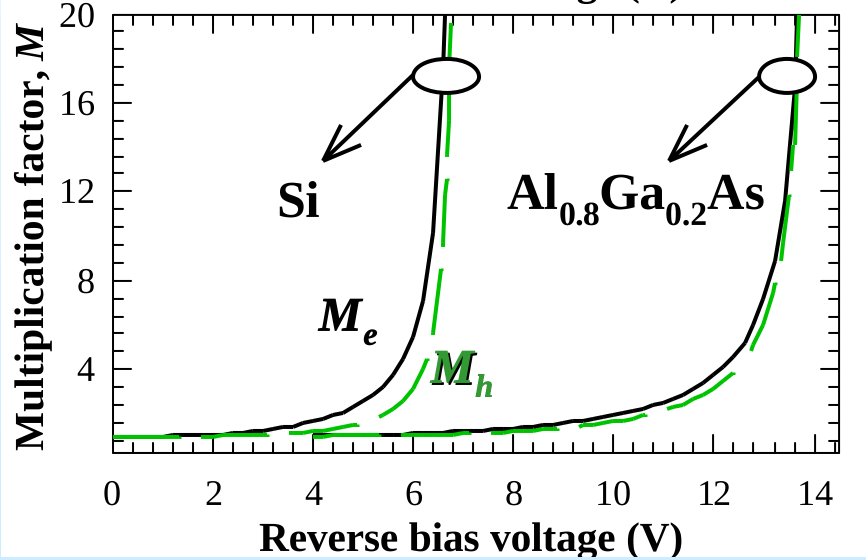
Reach-Through APDs

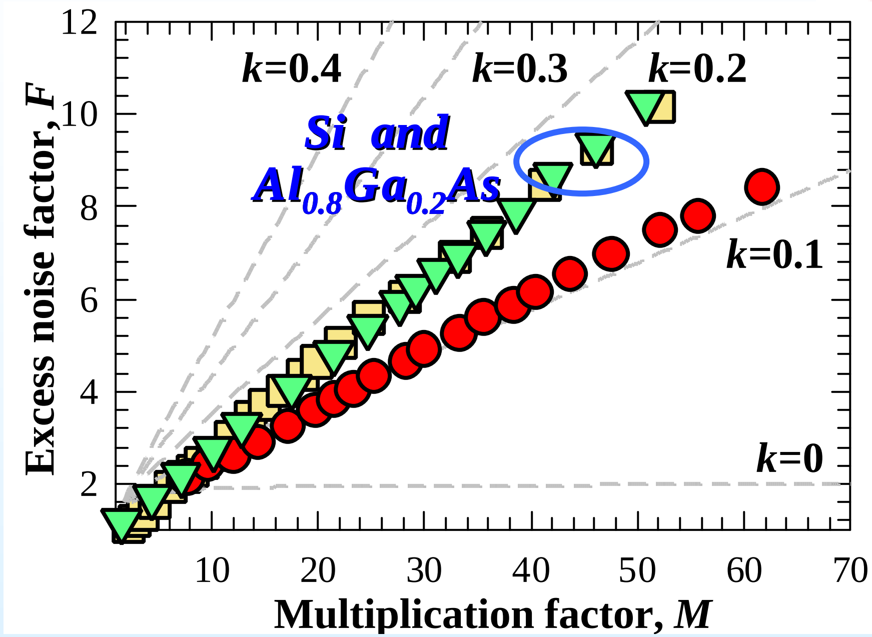


- **Excess noise measured for *M* > 40**
  - Þ ***good quality of APDs, very stable avalanche multiplication***
- **Very low excess noise of *k* = 0.1 & 0.15 measured with 365 nm light**
- **Excess noise from electron injection (230 nm) gave *k* = 0.8 & 2.8**

Comparison with Si & $Al_{0.8}Ga_{0.2}As$







- V_{bd} of 4H-SiC is 10´ & 5´ of Si & $Al_{0.8}Ga_{0.2}As$ respectively
- M_e & M_h closer for Si, $Al_{0.8}Ga_{0.2}As$
- 4H-SiC Þ lowest excess noise in a *w* = 0.1 mm structure

Conclusions

- **4H-SiC APD's exhibit good visible-blind performance**
- **Photomultiplication characteristics**
  - *Large M in excess of 200 measured*
  - *show unambiguously that* $\beta > \alpha$
  - β / α *ratio remains large in short devices*
- **Very low excess noise of *k* = 0.1 achieved with mainly holes-initiated multiplication**
- **4H-SiC is a suitable material for high-gain, low noise UV avalanche photodiodes**

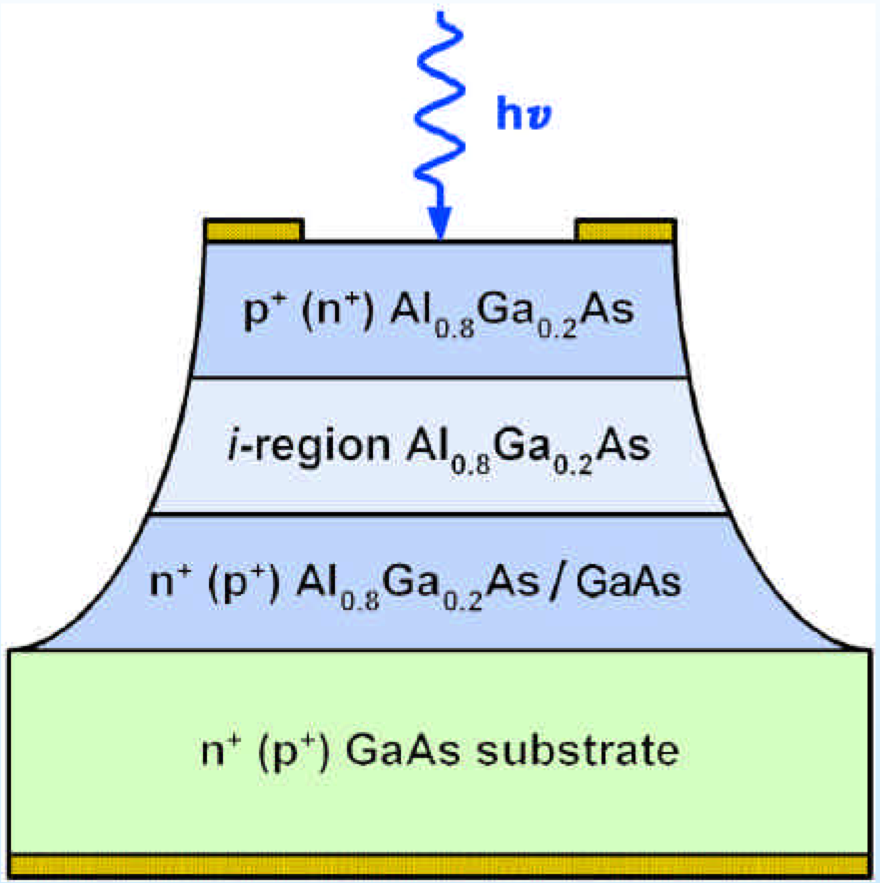
$Al_{0.8}Ga_{0.2}As$: *A Very Low Excess Noise Multiplication Medium for GaAs-based APDs*

Motivation

- $Al_xGa_{1-x}As$ material system is widely used in HBTs and IMPATTs
- Use in telecom wavelength APDs limited by lack of lattice-matched material that absorbs at long wavelength
- GaInAsN has recently been demonstrated
  - ☞ ***absorbs long wavelength***
  - ☞ ***lattice-matched to*** $Al_xGa_{1-x}As$
- GaAs-based APDs is possible and may require $Al_xGa_{1-x}As$ multiplication region for optimum performance

$Al_{0.8}Ga_{0.2}As$: *A Very Low Excess Noise Multiplication Medium for GaAs-based APDs*

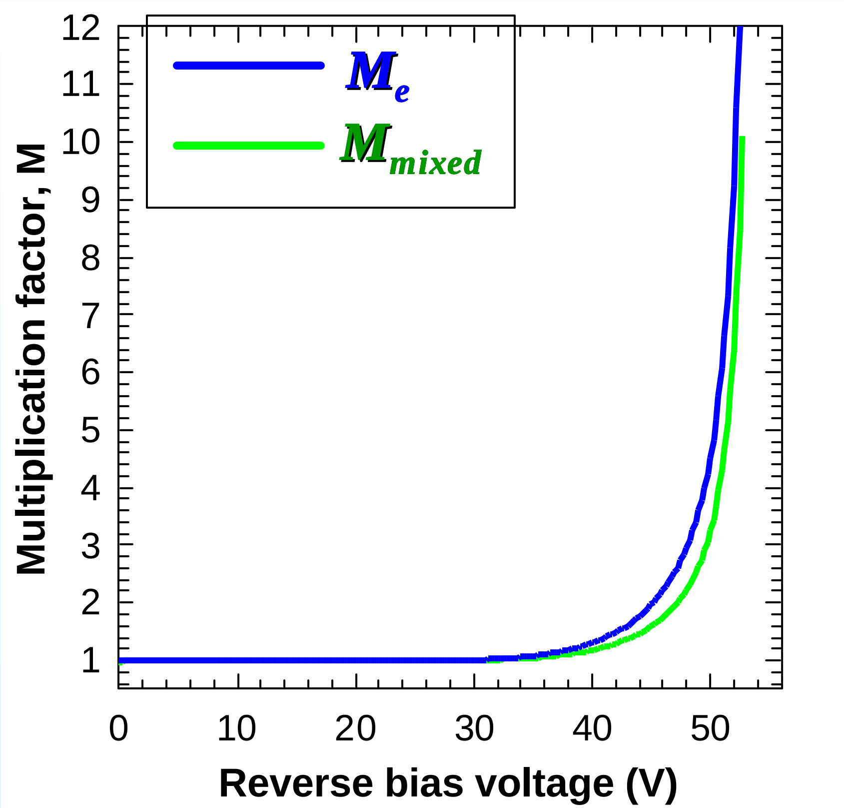
Device structures

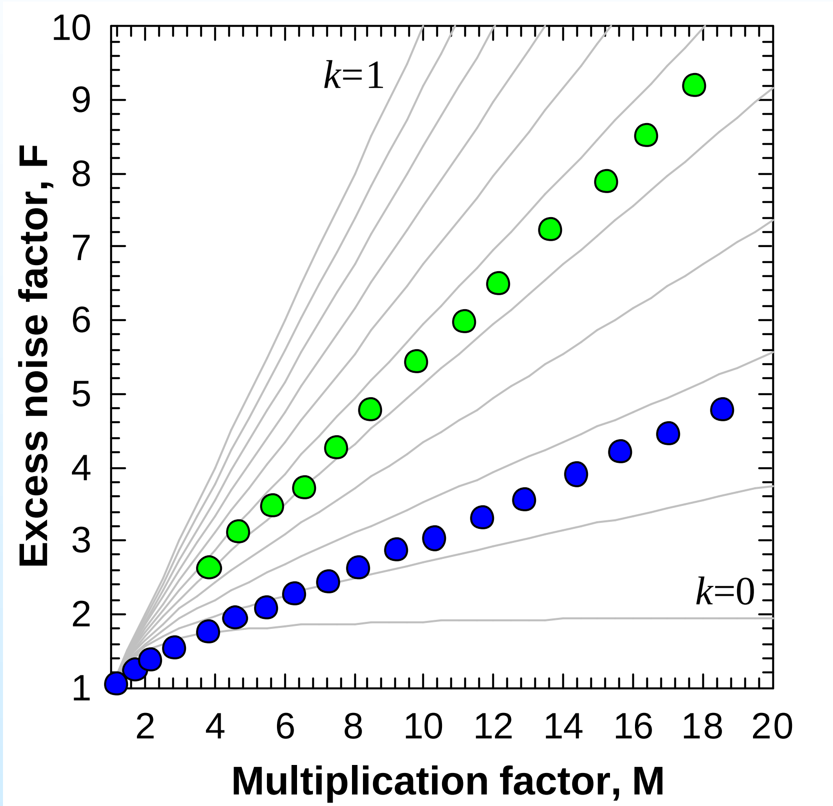


- **Homojunction p-i-n/n-i-p grown by conventional MBE with *w* = 1 mm**
- **1 heterojunction p-i-n with *w*=0.8 mm to obtain M_e & M_h from same diode**
- **Optical access window fabricated by wet etching**
- **Pure carrier injection obtained with 442nm & 633nm light**
- **542nm light used to produce mixed carrier injection**

$Al_{0.8}Ga_{0.2}As$: *A Very Low Excess Noise Multiplication Medium for GaAs-based APDs*

Avalanche excess noise of homojunction p-i-n diodes



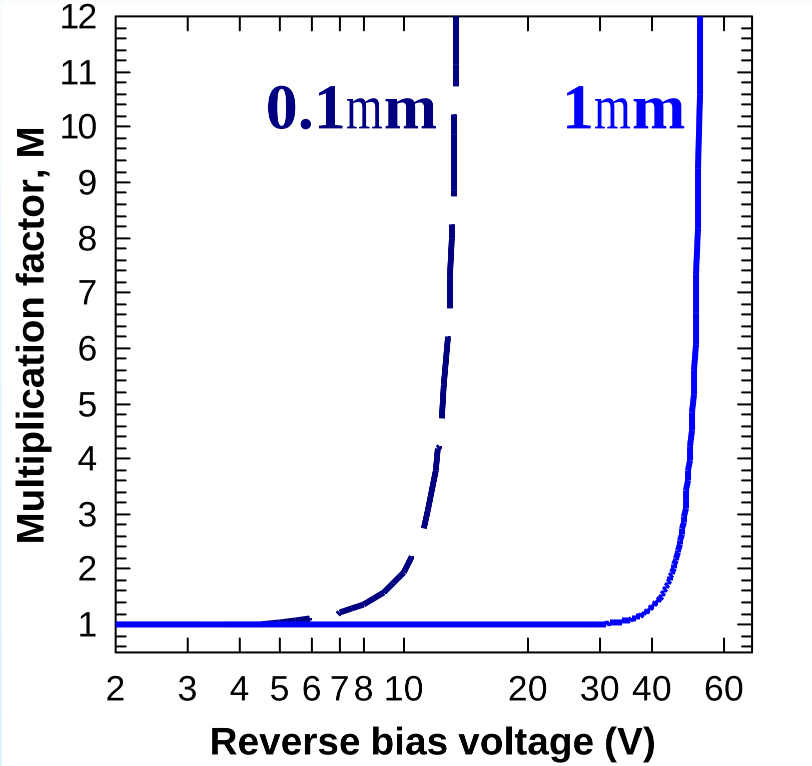


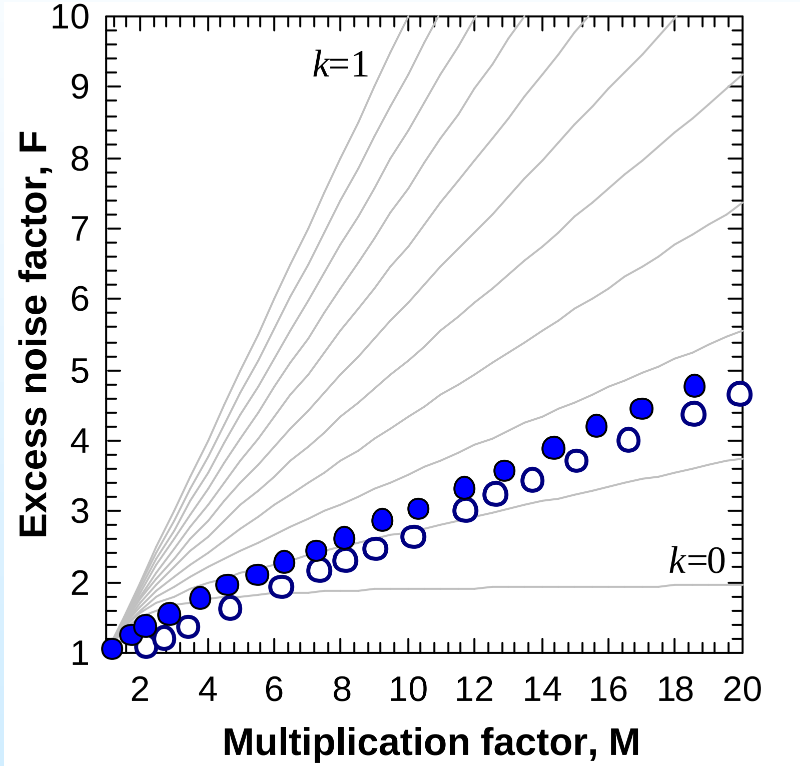
- **Lower *M* for mixed carrier injection** Þ a > b

- ***k*~ 0.19 for electron multiplication**
- **Larger *F* for mixed carrier injection**

$Al_{0.8}Ga_{0.2}As$: A Very Low Excess Noise Multiplication Medium for GaAs-based APDs

Avalanche excess noise of thin diodes



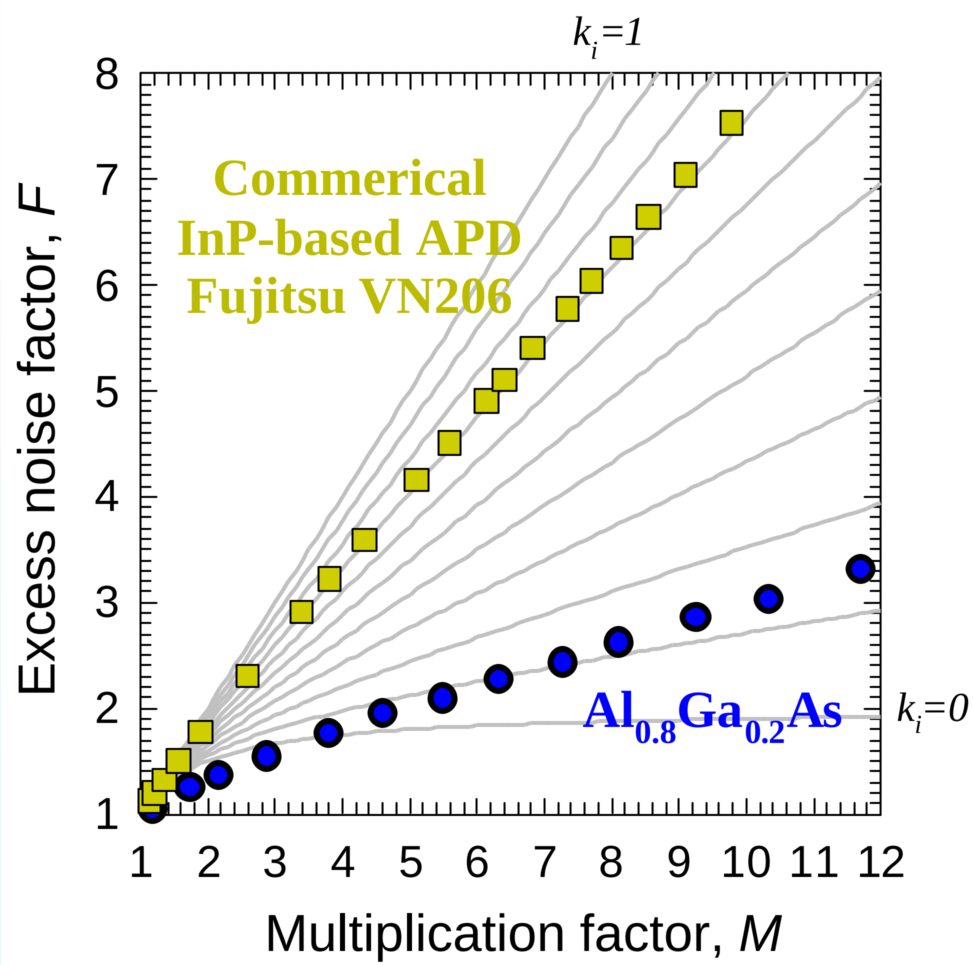


- **V_{bd} ¯ with decreasing *w***

- **Comparable excess noise for bulk and thin diodes**

$Al_{0.8}Ga_{0.2}As$: A Very Low Excess Noise Multiplication Medium for GaAs-based APDs

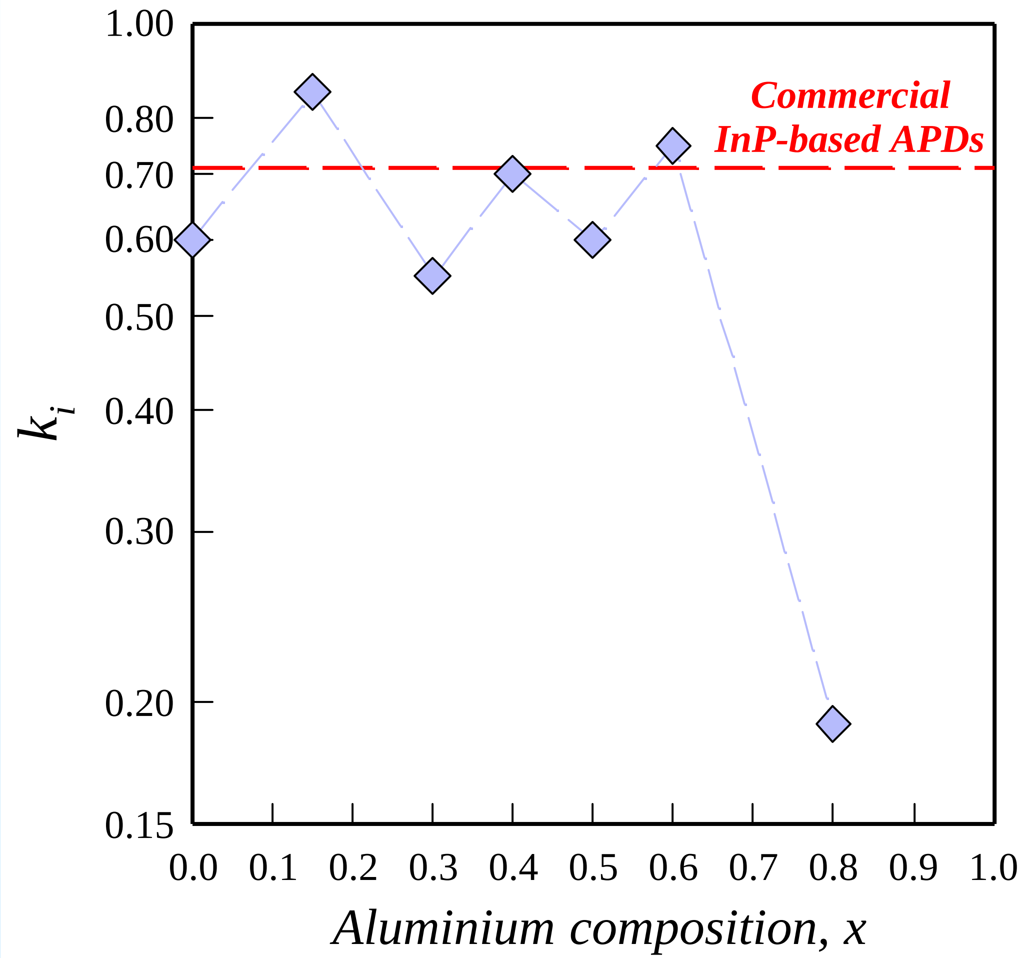
Comparison with InP-based APDs



- **Commercial InP-based APD give excess noise of k_i=~0.7 with hole initiated multiplication**
- **Much lower excess noise can be obtained with $Al_{0.8}Ga_{0.2}As$ as avalanche medium**

$Al_{0.8}Ga_{0.2}As$: A Very Low Excess Noise Multiplication Medium for GaAs-based APDs

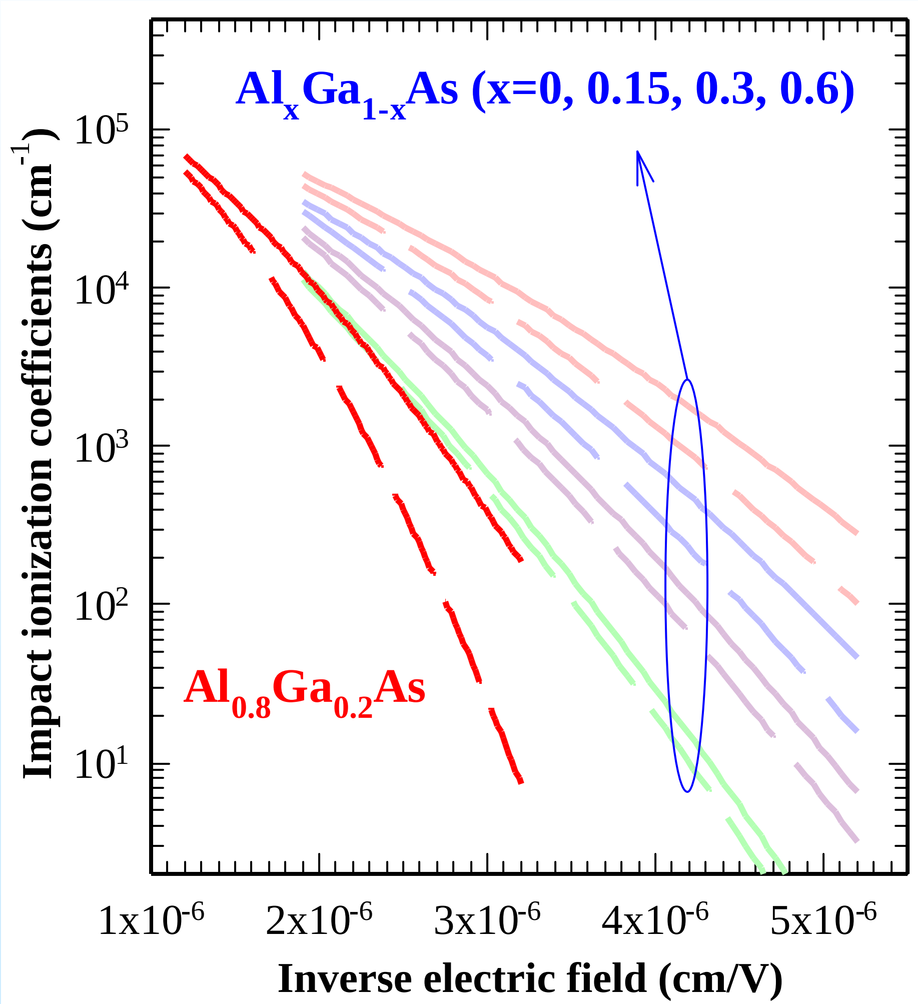
Comparison with lower aluminium $Al_xGa_{1-x}As$



- **$Al_xGa_{1-x}As$ (x £ 0.6) has large avalanche excess noise**
- **Excess noise of $Al_{0.8}Ga_{0.2}As$ is much lower**
- **$Al_{0.8}Ga_{0.2}As$ also has lower excess noise than a commercial InP-based APD**
- **At M=10, excess noise of $Al_{0.8}Ga_{0.2}As$ is at least 2 times lower**

$Al_{0.8}Ga_{0.2}As$: A Very Low Excess Noise Multiplication Medium for GaAs-based APDs

Ionization coefficients



- **Large** a/b **ratio as compared to $Al_xGa_{1-x}As$ of lower *x***
  Þ ***Lower excess noise***

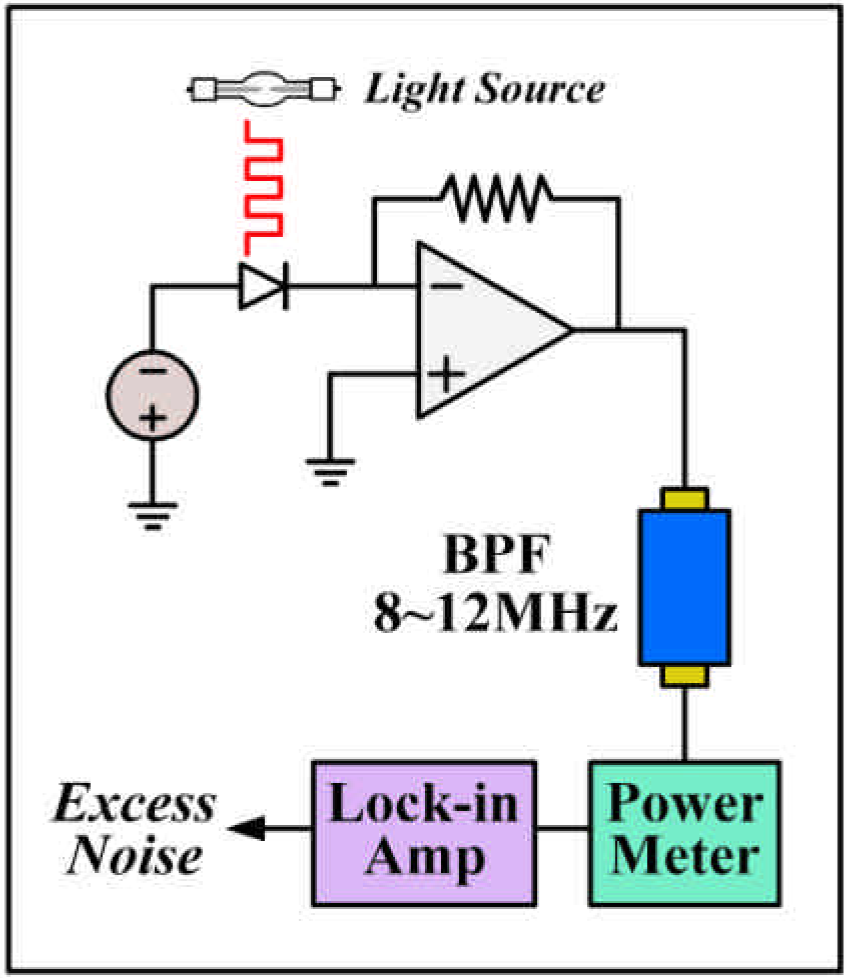
- b/a **ratio of InP is small**
  Þ ***Higher excess noise***

$Al_{0.8}Ga_{0.2}As$: A Very Low Excess Noise Multiplication Medium for GaAs-based APDs

Conclusions

- ☞ ***Bulk $Al_{0.8}Ga_{0.2}As$ diodes give lower excess noise than $Al_xGa_{1-x}As$ (x £ 0.6) or InP***
- ☞ ***Consequence of the larger a/b ratio in $Al_{0.8}Ga_{0.2}As$***
- ☞ ***Low noise APDs may be achievable on GaAs substrates using $Al_{0.8}Ga_{0.2}As$ as the gain medium***

APD noise measurement system



Excess noise

- ***10 MHz center frequency***
- ***ENBW of 4 MHz***
- ***AC technique with modulated light source***
- ***F from M & noise power***
- ***Shot noise of Si p-i-n as reference***