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Research Workshop on Condensed Matter Physics
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MINIWORKSHOP ON
QUANTUM WELLS, DOTS, WIRES
AND SELF-ORGANIZING NANOSTRUCTURES
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"Many Body Effects in 2D-0D Tunnelling"

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These are preliminary lecture notes, intended only for distribution to participants.

MANY BODY EFFECTS IN 2D-0D TUNNELLING

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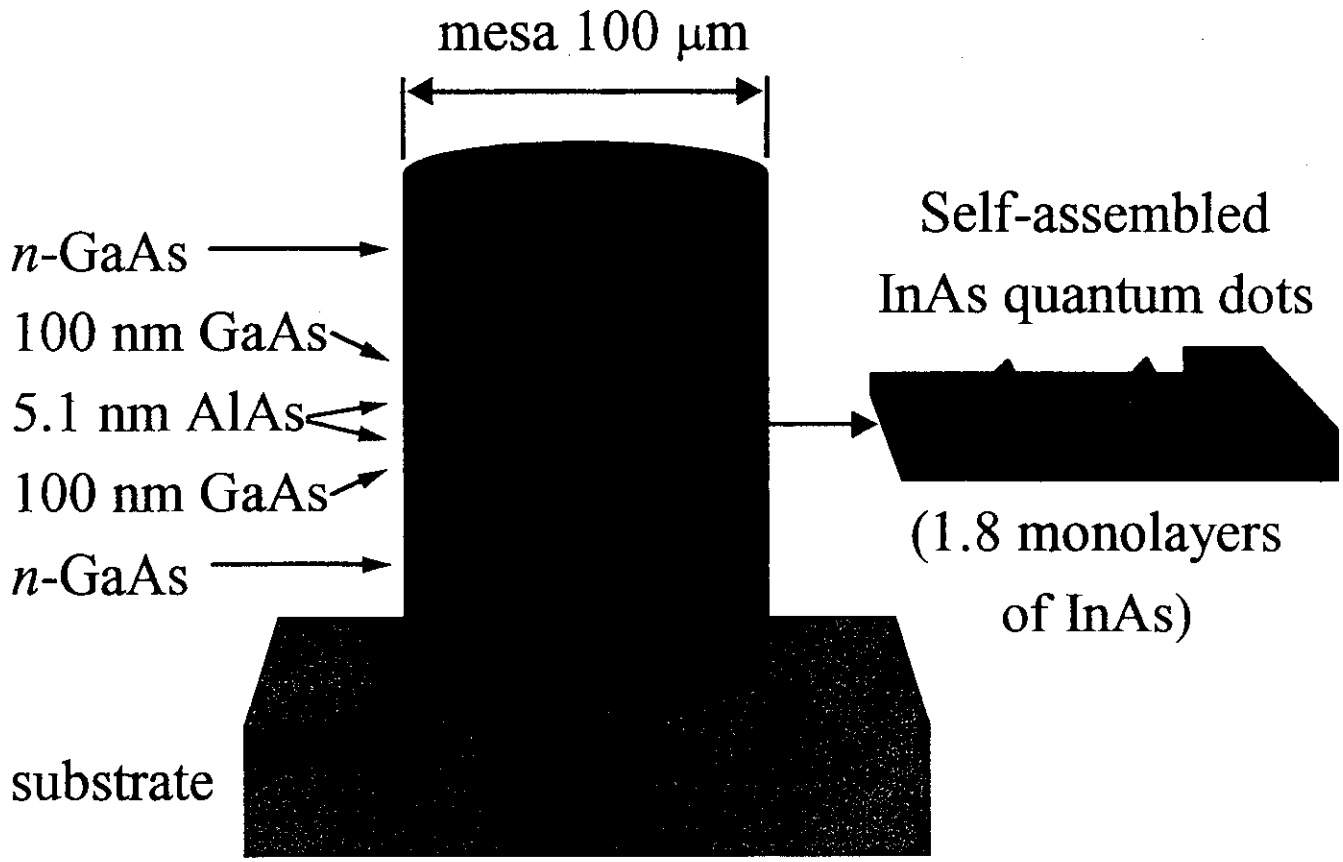
A SELF-ORGANISED QUANTUM DOT ACTS AS A ZERO-DIMENSIONAL TUNNELLING CHANNEL. THE TUNNEL CURRENT FROM THE EMITTER 2DEG:

- **DENSITY OF STATES BELOW THE FERMI ENERGY**
- **MANY-BODY EFFECTS**
- **LANDAU-LEVEL BROADENING AND QUASIPARTICLE LIFETIME**
- **SPIN-POLARISATION**
- **COMPOSITE FERMION EFFECTS** ?

SAMPLE

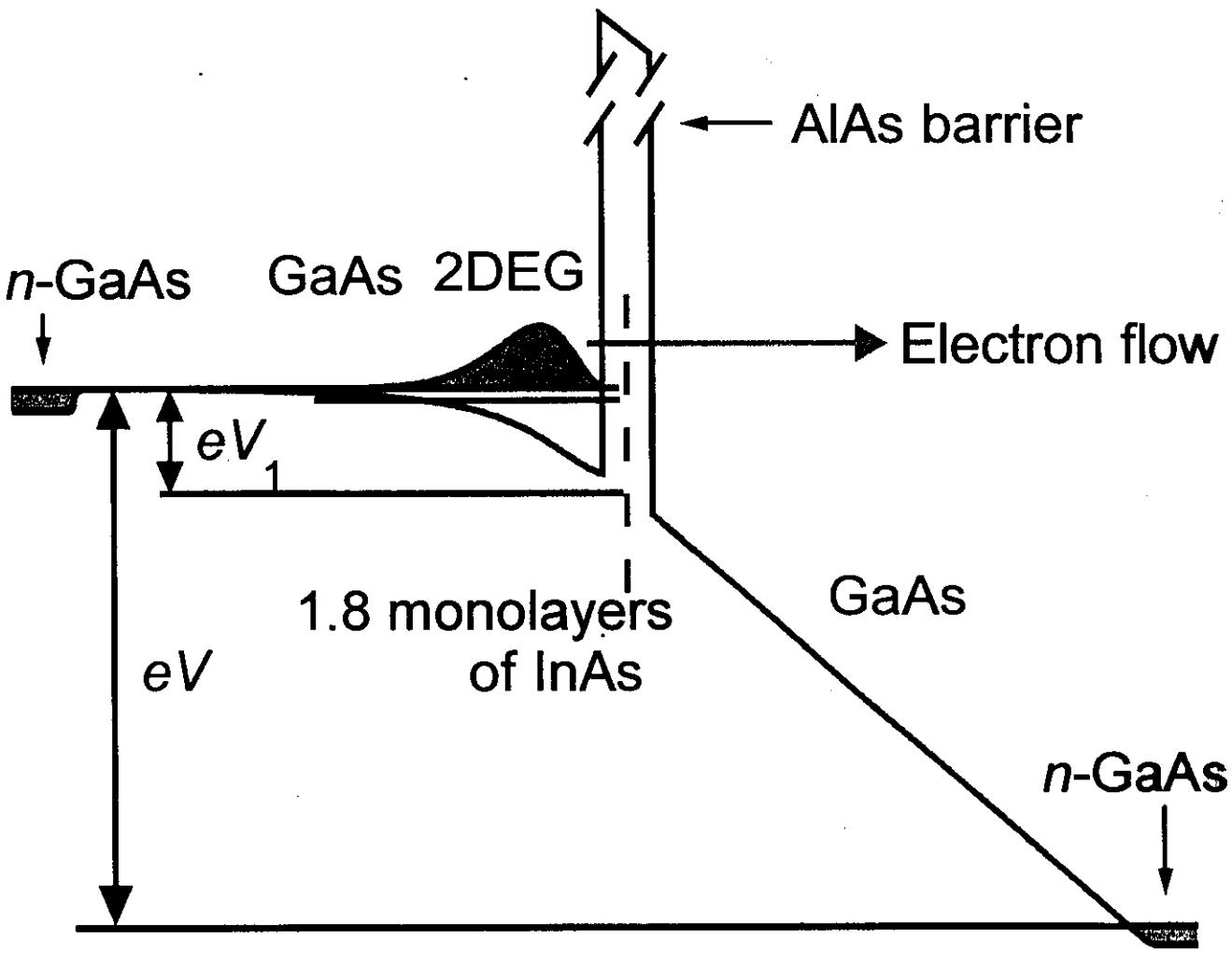
A single-barrier tunnelling heterostructure device



Total width of AlAs barrier - 10.2 nm

InAs layer has been grown in the middle of the barrier

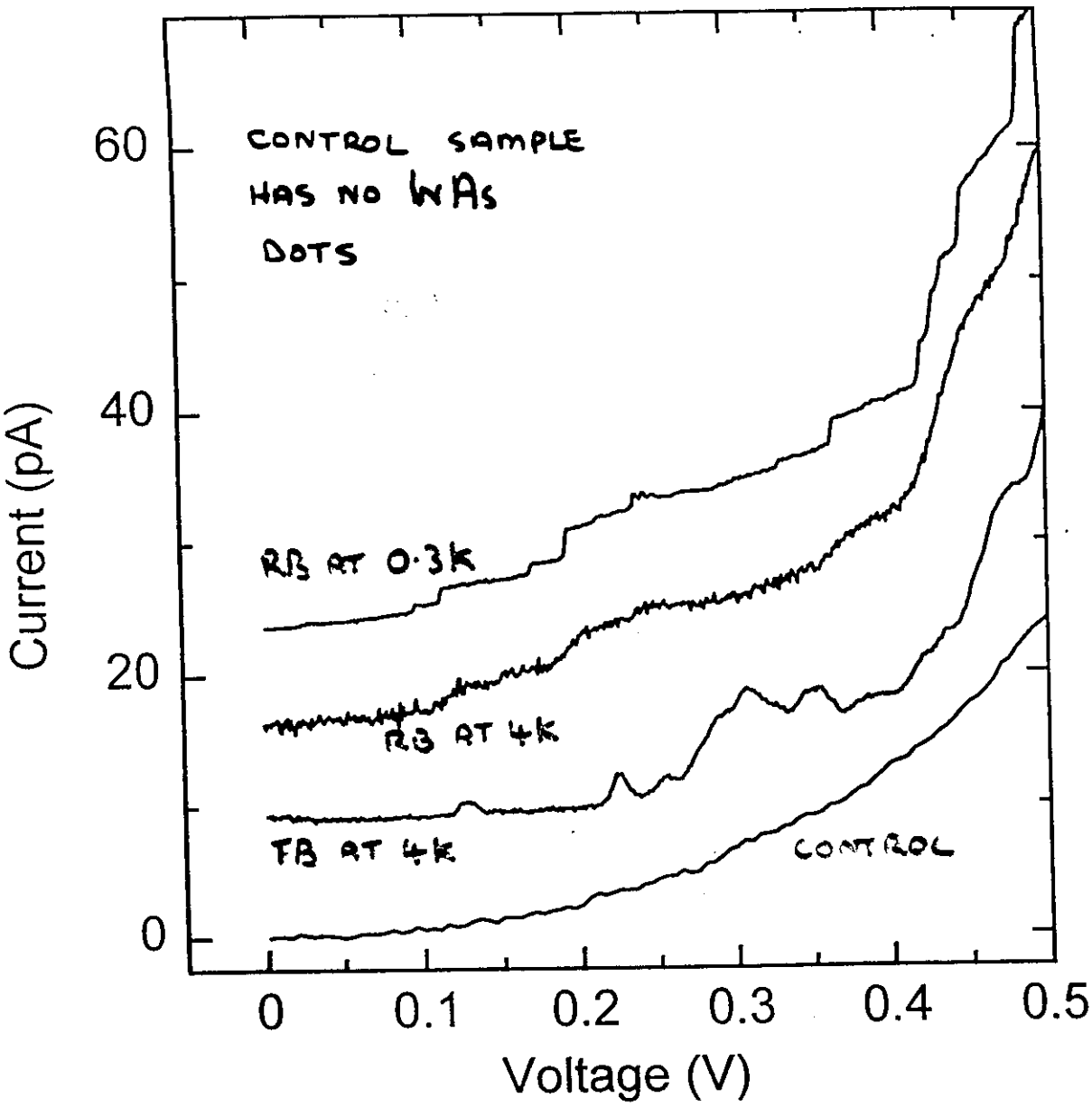
CONDUCTION BAND: POTENTIAL PROFILE

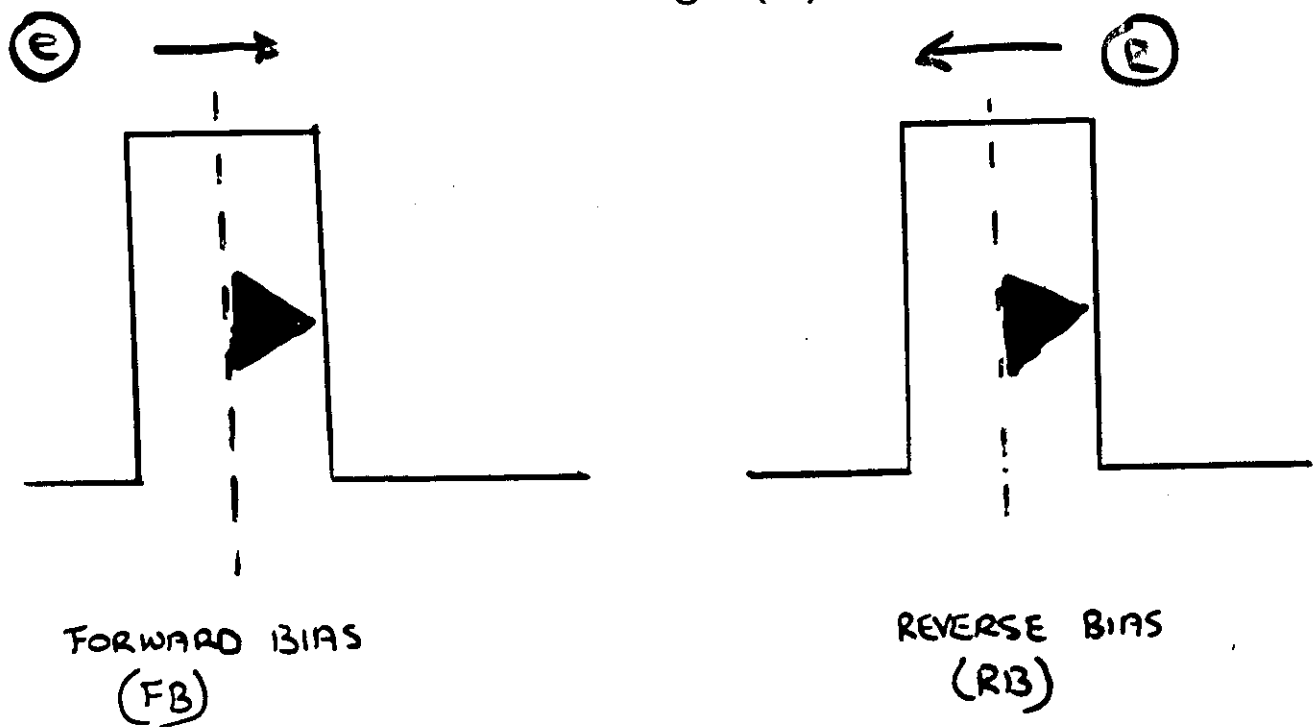


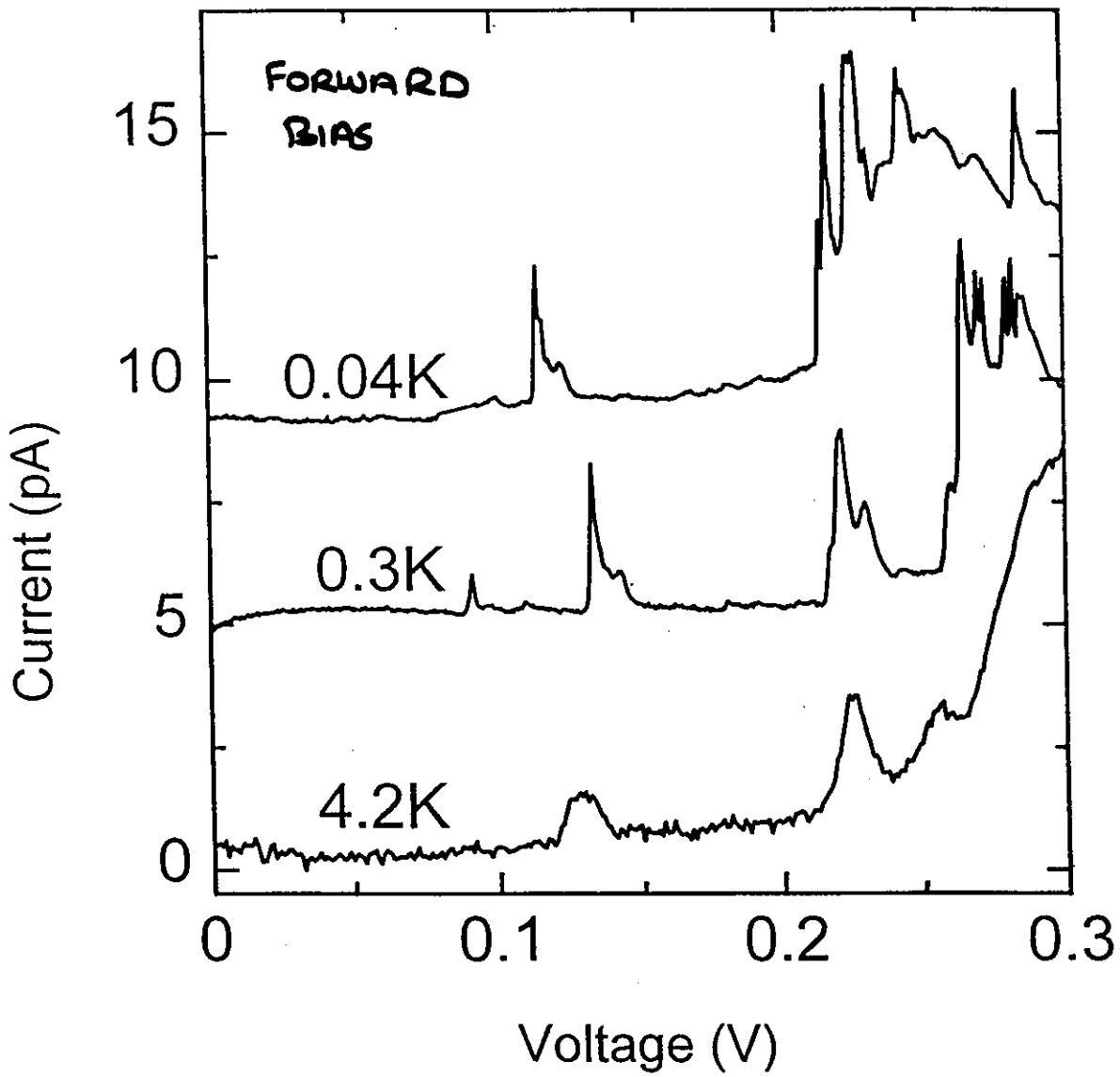
eV - external bias; eV_1 - voltage drop between 2DEG and quantum dot layer

$f=(dV_1/dV)^{-1}$ - electrostatic leverage factor

Resonant tunnelling occurs when a state in the barrier is resonant with a state in the 2DEG


CONTROL SAMPLE
HAS NO InAs
DOTS
RB AT 0·3K
RB AT 4K
FB AT 4K
CONTROL
Current (pA)
Voltage (V)
0
20
40
60
0
0.1
0.2
0.3
0.4
0.5

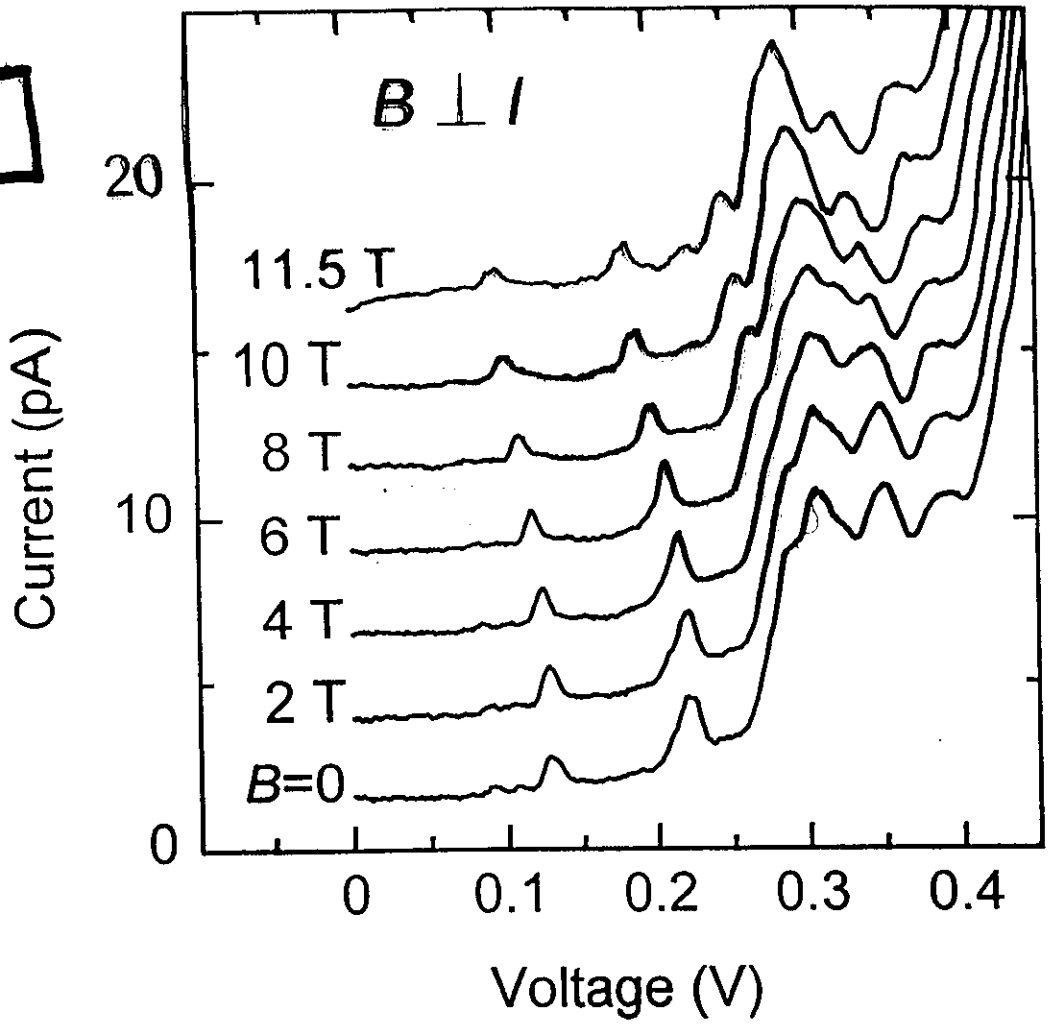

e
e
FORWARD BIAS
(FB)
REVERSE BIAS
(RB)

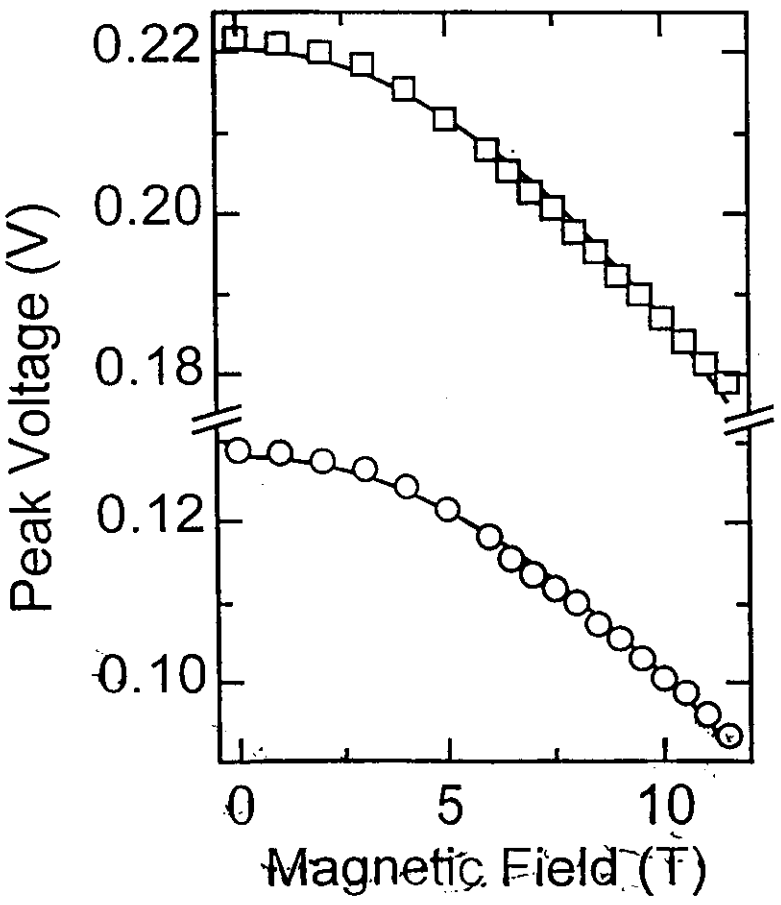


* T LIMITED CURRENT ONSET

* FERMI - EDGE SINGULARITY

T = 4.2K





* DIFFERENCE IN DIAMAGNETIC SHIFTS OF 2DEG AND QUANTUM DOT

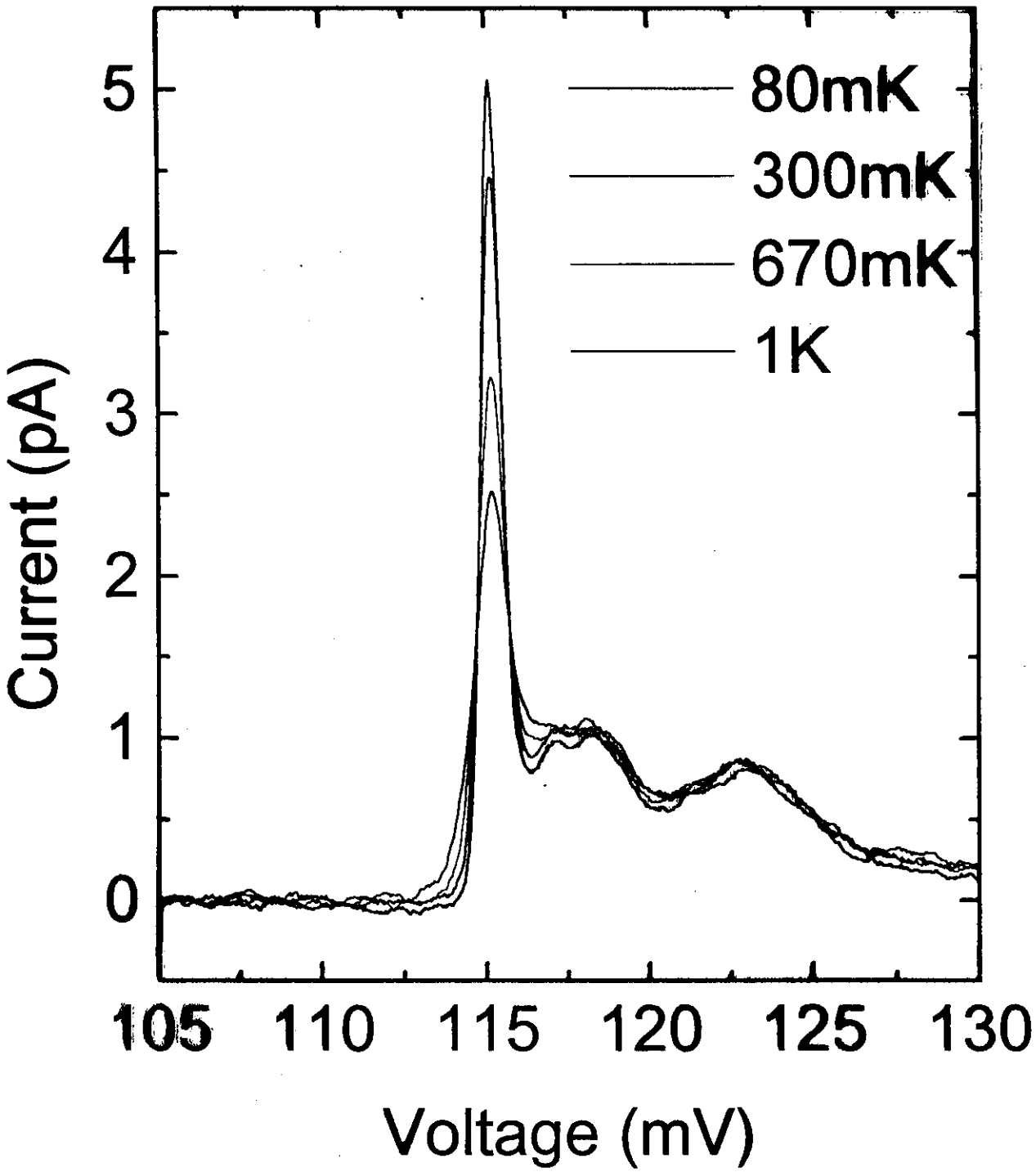
$\Rightarrow$ 10 ± 5 nm

$$\gamma \frac{f e^2 B^2}{2} \frac{\langle z^2 \rangle}{m^*}$$

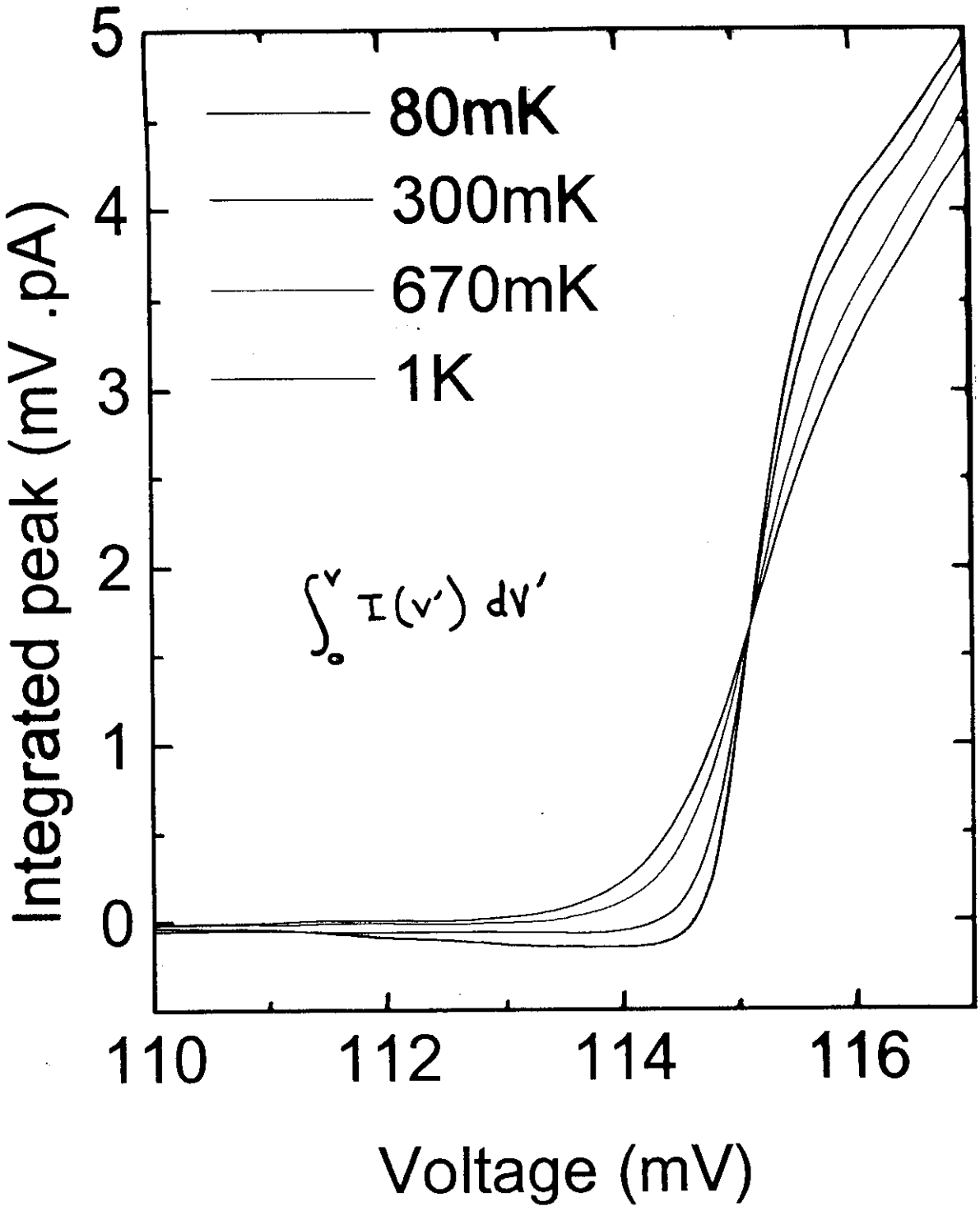
$0.5 < \gamma < 1$ [shape]

m^* ??

f - leverage

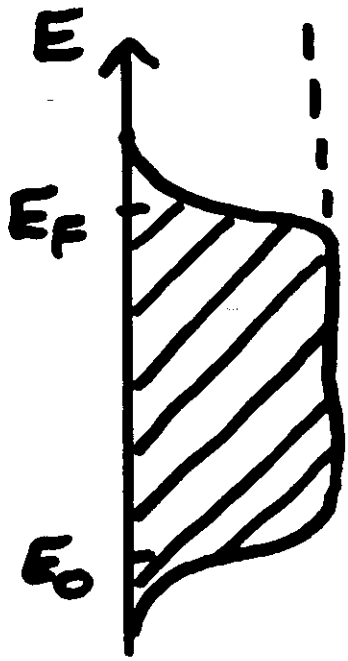


* FERMI-EDGE SINGULARITY IN I(V)
* OCCURS WHEN 0D STATE OF THE QUANTUM DOT IS RESONANT WITH E_F IN THE EMITTER
* DUE TO MANY-BODY EFFECTS GIVING RISE TO EXTRA TUNNELLING CHANNELS AT LOW TEMPERATURES.



* INTEGRATED AREA UNDER CURVE DEPENDS ON T
* SMEARING OF FEATURE EXTENDS MANY $k_B T$ BELOW ONSET
* CROSSING POINT (X) IS AT VOLTAGE OF PEAK

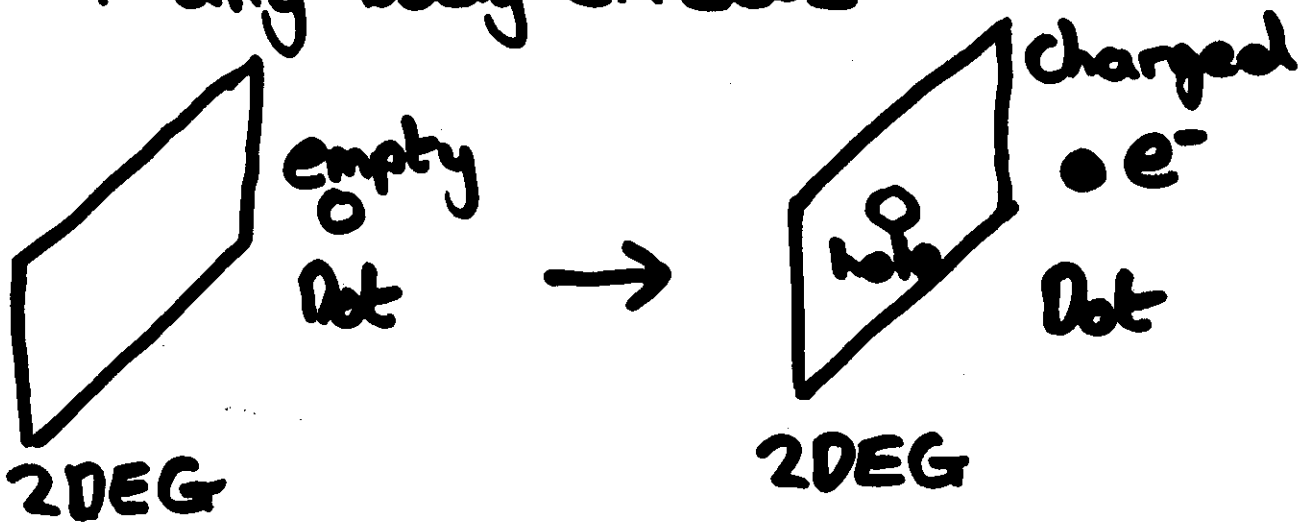
Single Particle effects

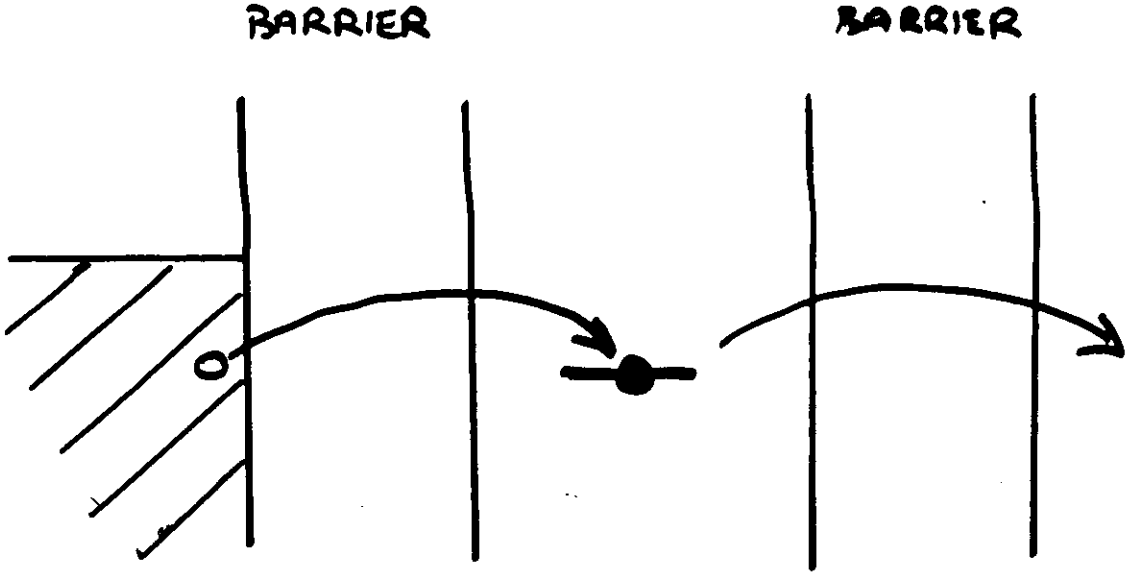


2DEG

B=0

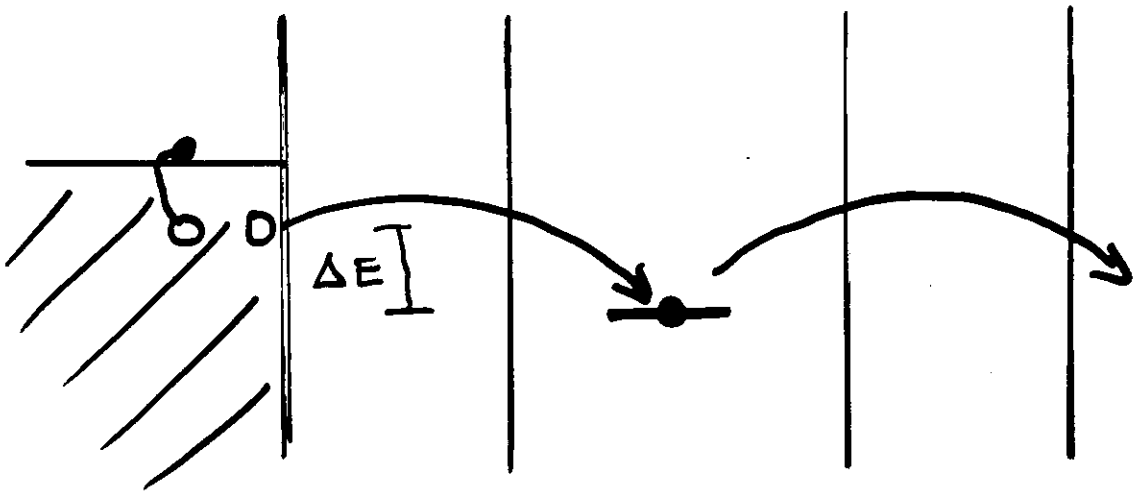
Many body effects





FIRST ORDER PROCESS

* ONLY RESONANT TUNNELLING ALLOWED



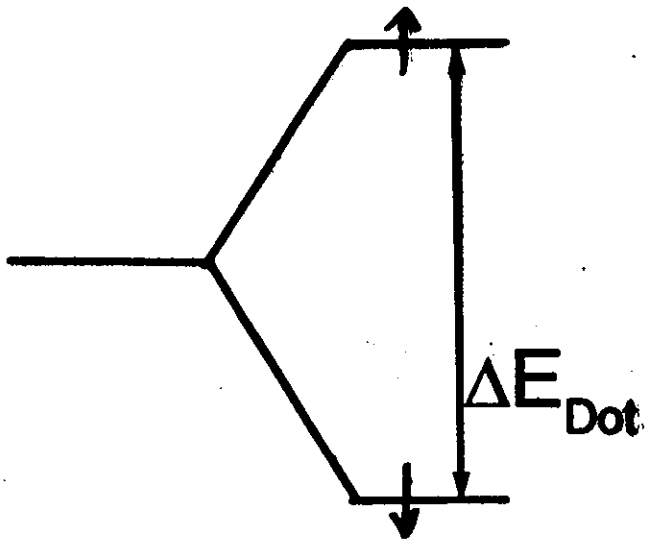
SECOND ORDER PROCESS

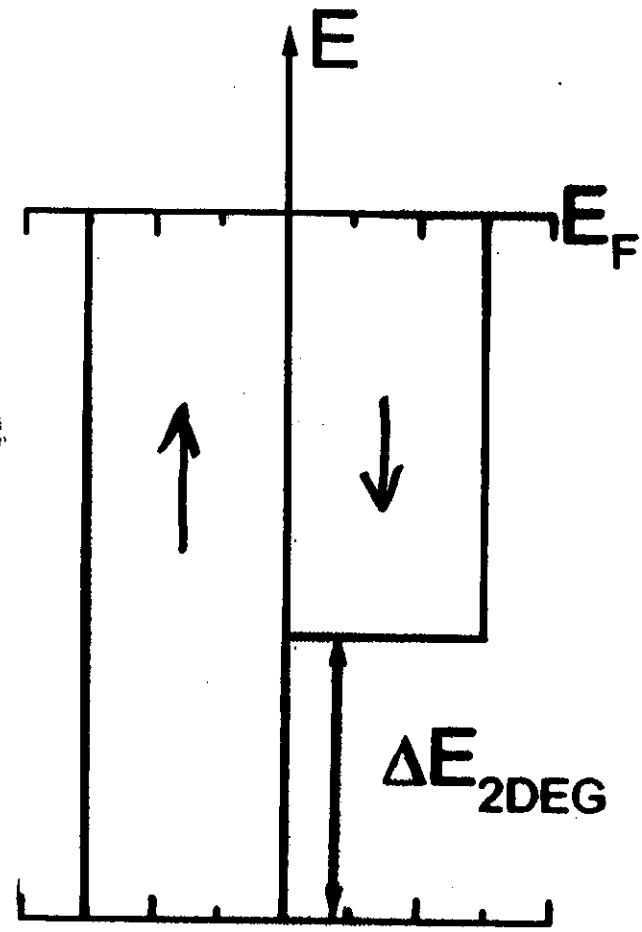
FERMI-EDGE SINGULARITY IS DUE TO SECOND ORDER PROCESSES.

[SMALL ENERGY TRANSFER PREFERRED BY FERMI'S GOLDEN RULE AND ONLY STATES UNOCCUPIED ARE NEAR E_f]

EXTRA WEIGHT $\sim \frac{W_0^2 U_0}{\Delta E}$

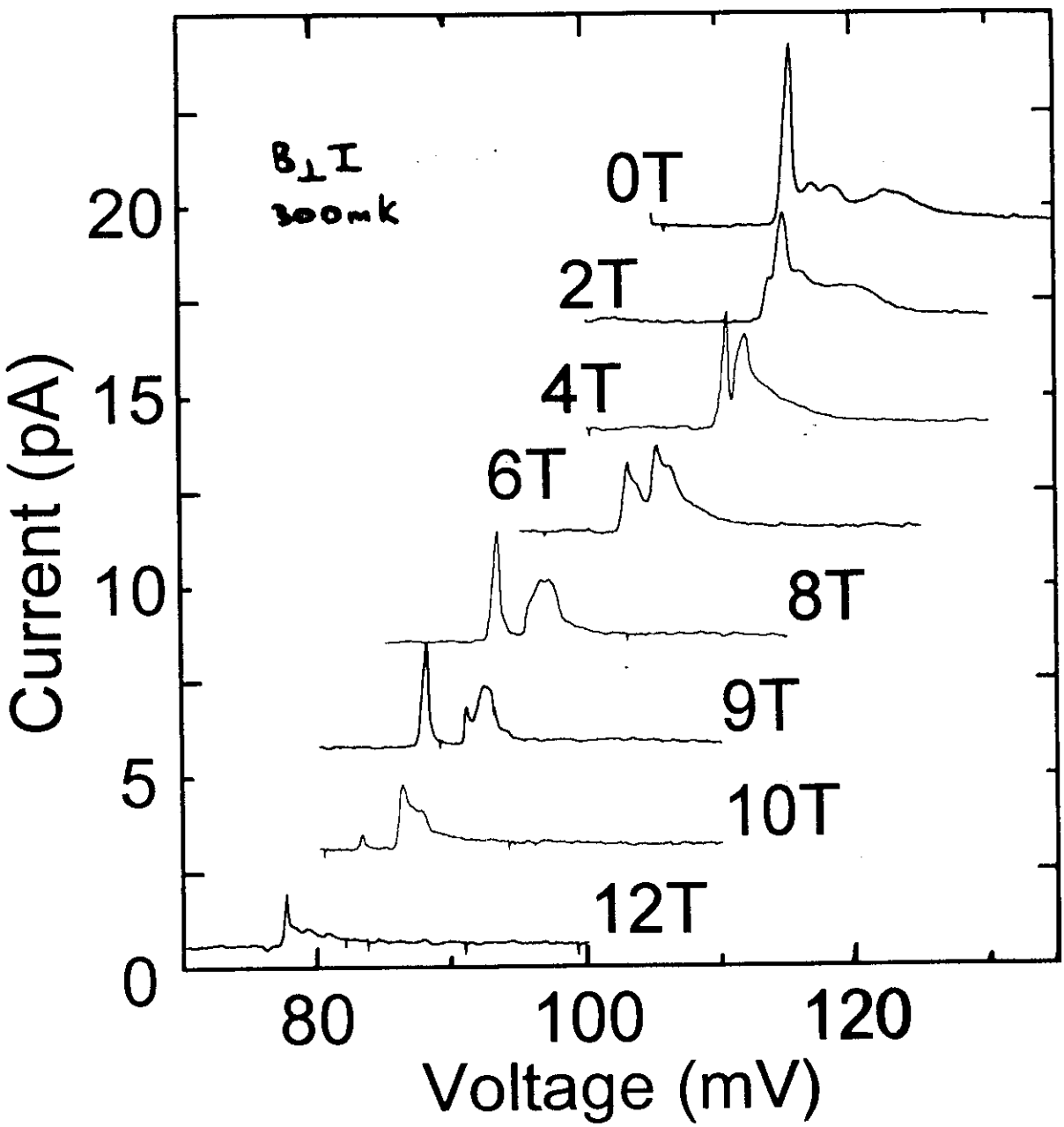
W_0^2 - matrix element
U_0 - interaction strength

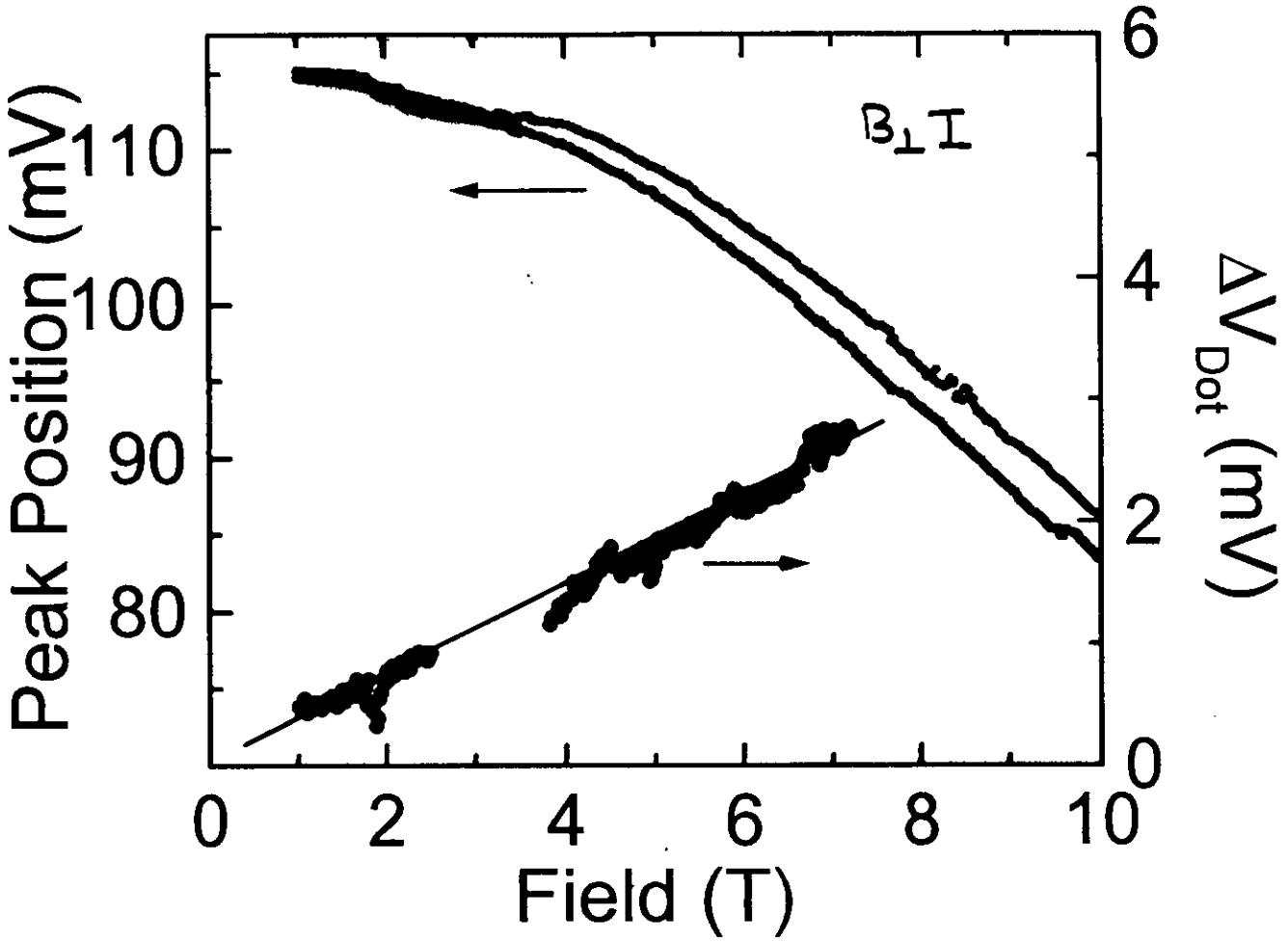




$$\Delta E_{Dot} = g_{Dot} \mu_B B$$

$$\Delta E_{2DEG} = g_{2DEG} \mu_B B$$


B⊥I
300mk
0T
2T
4T
6T
8T
9T
10T
12T
Current (pA)
0
5
10
15
20
80
100
120
Voltage (mV)

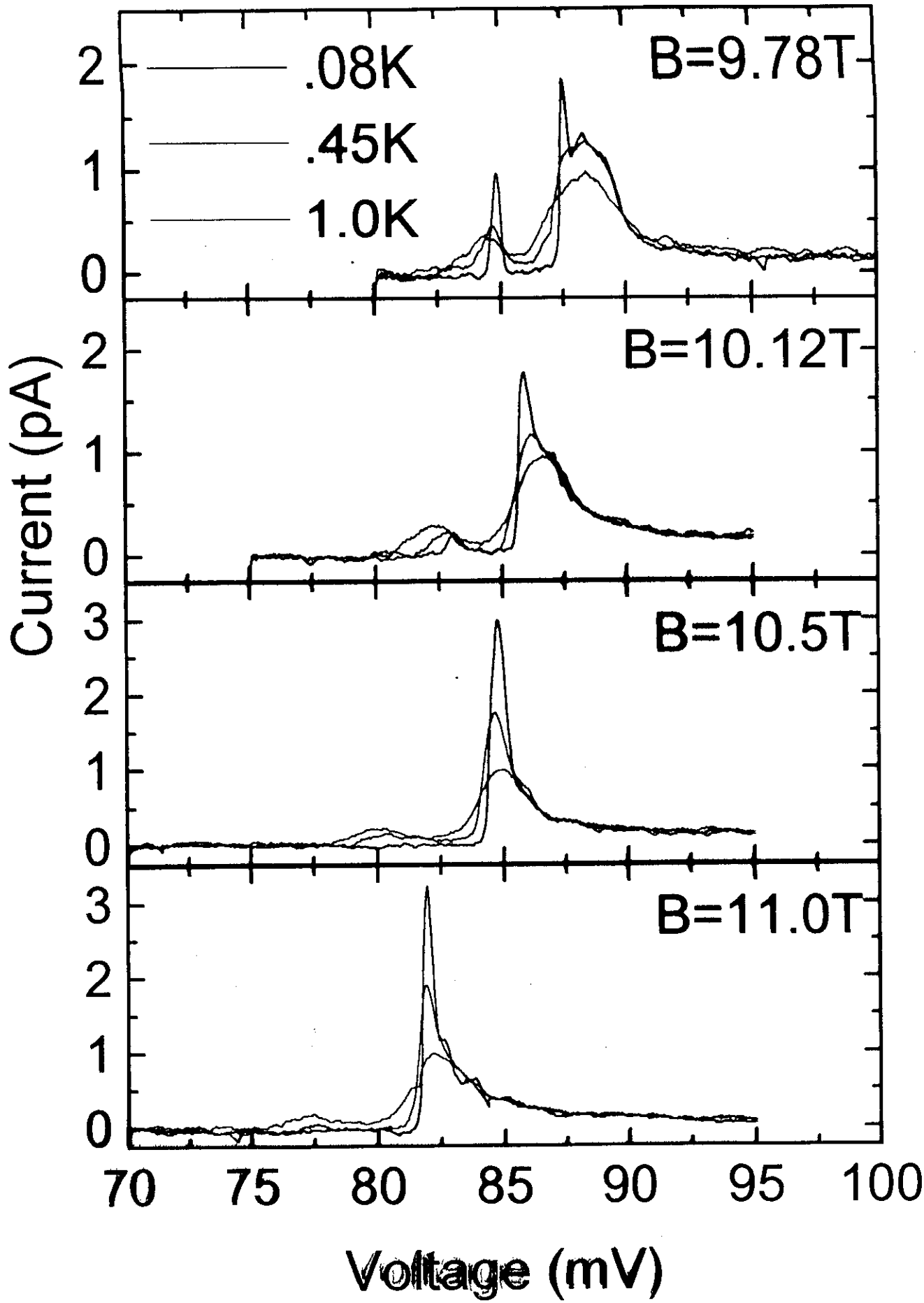


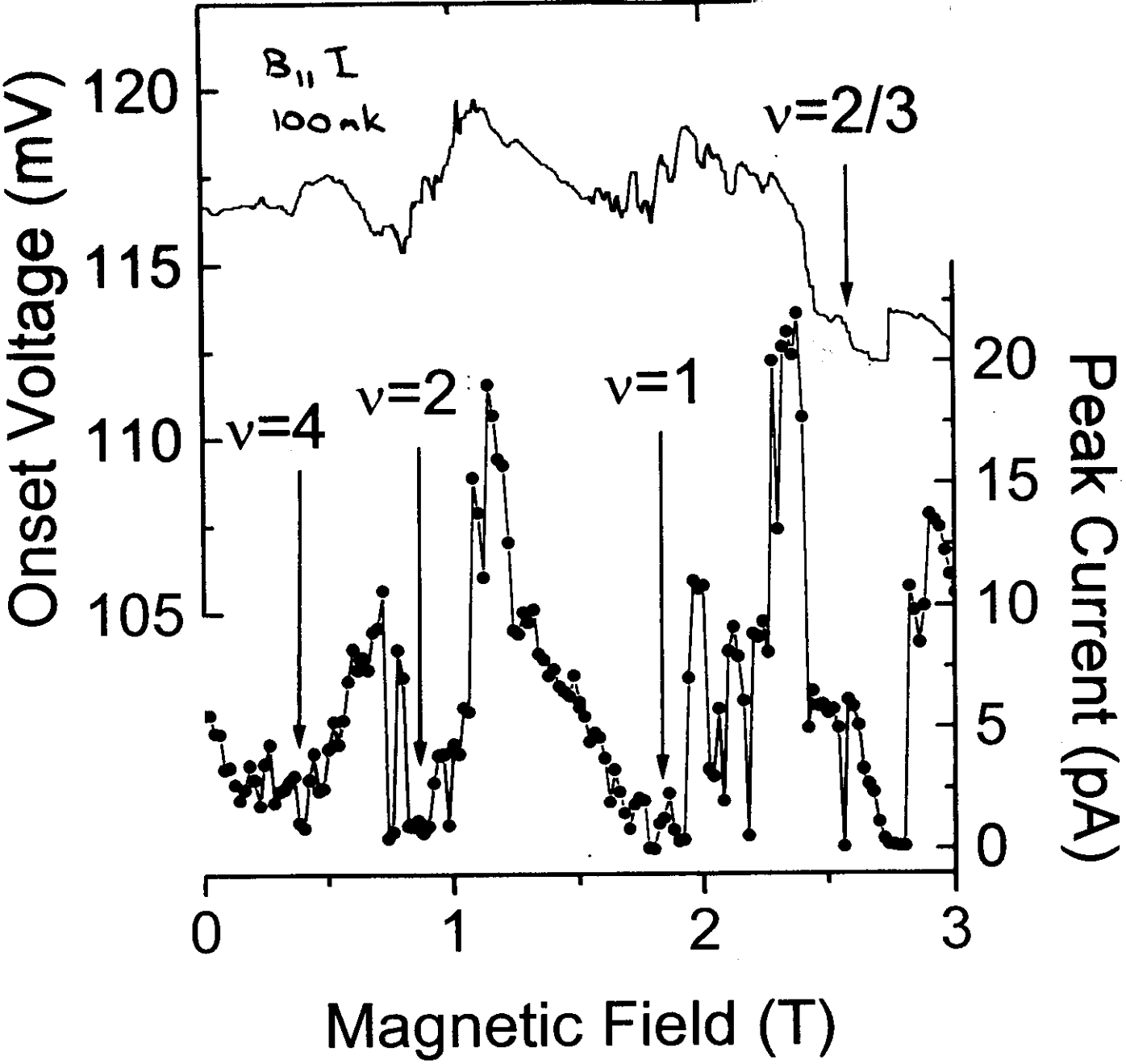
g^* (QUANTUM DOT) $\approx +1\ (\pm 0.2)$

[Γ_{cf} -14 in bulk InAs]

g^* (2DEG) ≈ -0.5

[Note sign difference]

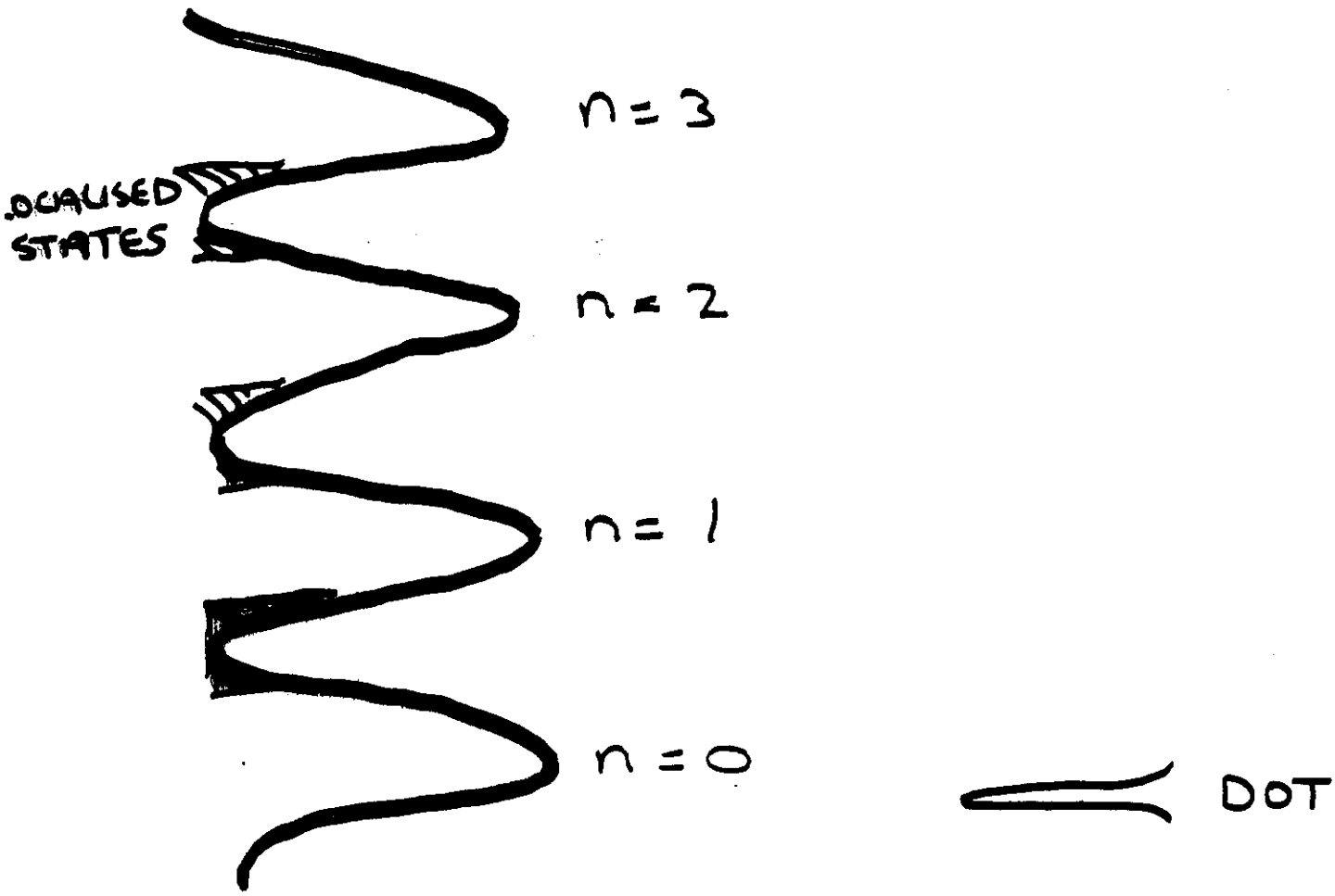

.08K
.45K
1.0K
B=9.78T
B=10.12T
B=10.5T
B=11.0T
Current (pA)
Voltage (mV)
0
1
2
3
70
75
80
85
90
95
100

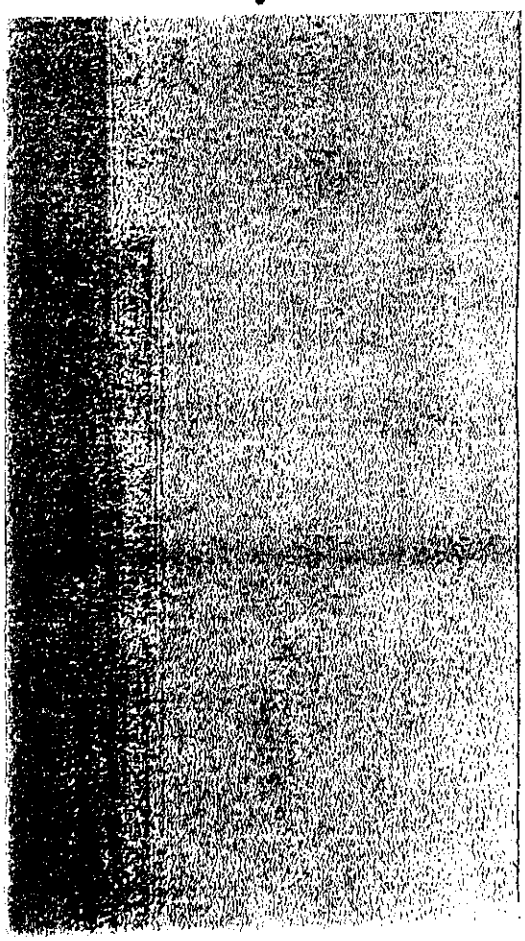


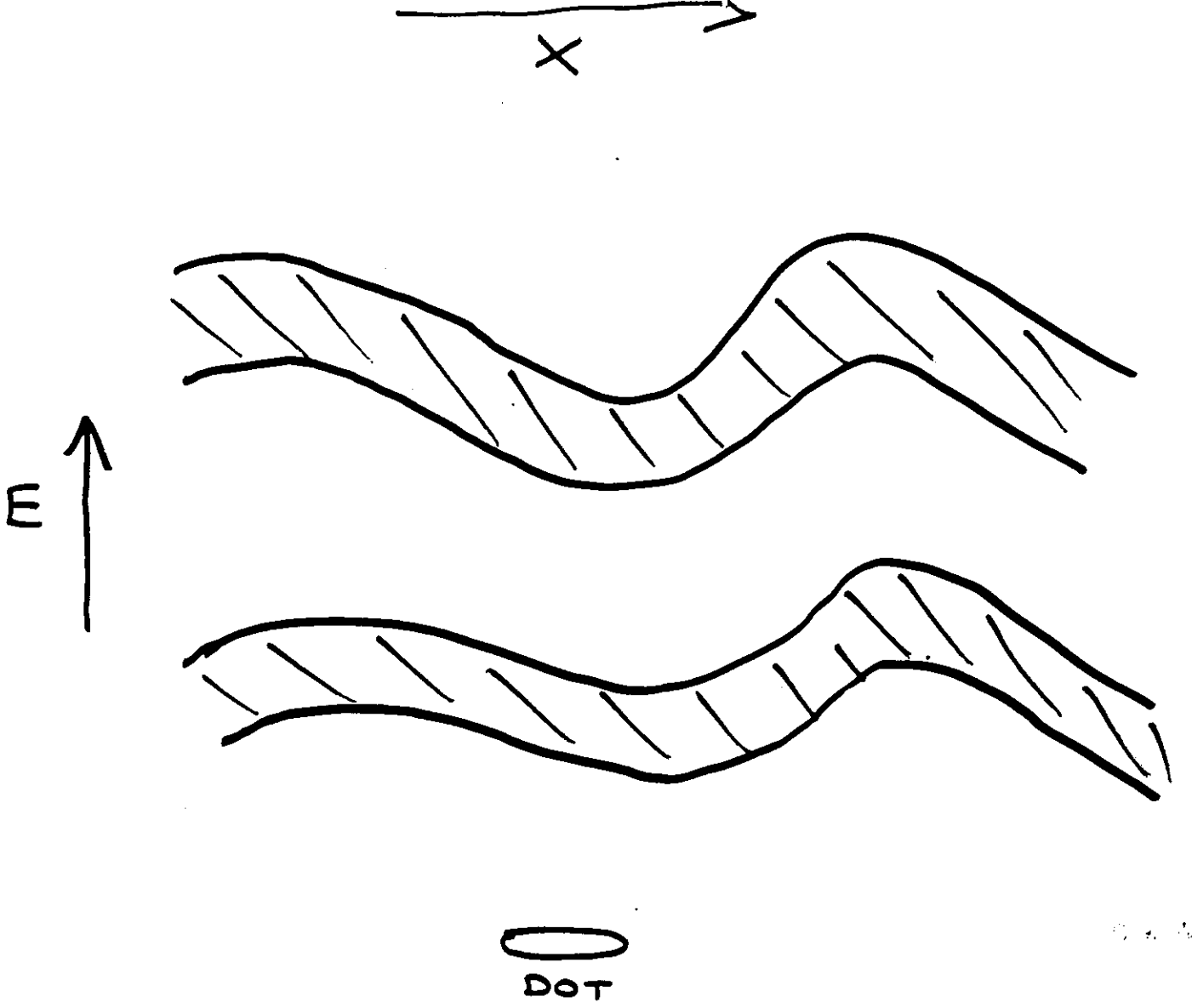
* ONSET VOLTAGE IS DEFINED AS WHEN THE CURRENT REACHES ITS "SINGLE PARTICLE" VALUE (SAY 1pA)

* ONSET VOLTAGE RELATED TO CHEMICAL POTENTIAL OF 2DEG

* NOTE FES PERSISTS IN MAGNETIC FIELD BUT IT COLLAPSES AT INTEGER FILLING FACTORS


n = 3
LOCALISED STATES
n = 2
n = 1
n = 0
DOT





* DOT IS A LOCAL PROBE OF DENSITY OF STATES
* LENGTH SCALE IS (?) LOCALISATION LENGTH
* LOCALISATION LENGTH IS A STRONG FUNCTION OF P

FES IN A MAGNETIC FIELD

$$I \propto \rho(\varepsilon_F)\,(\varepsilon_F - \varepsilon_d)^{-\Omega \rho(\varepsilon_F) V_0}$$

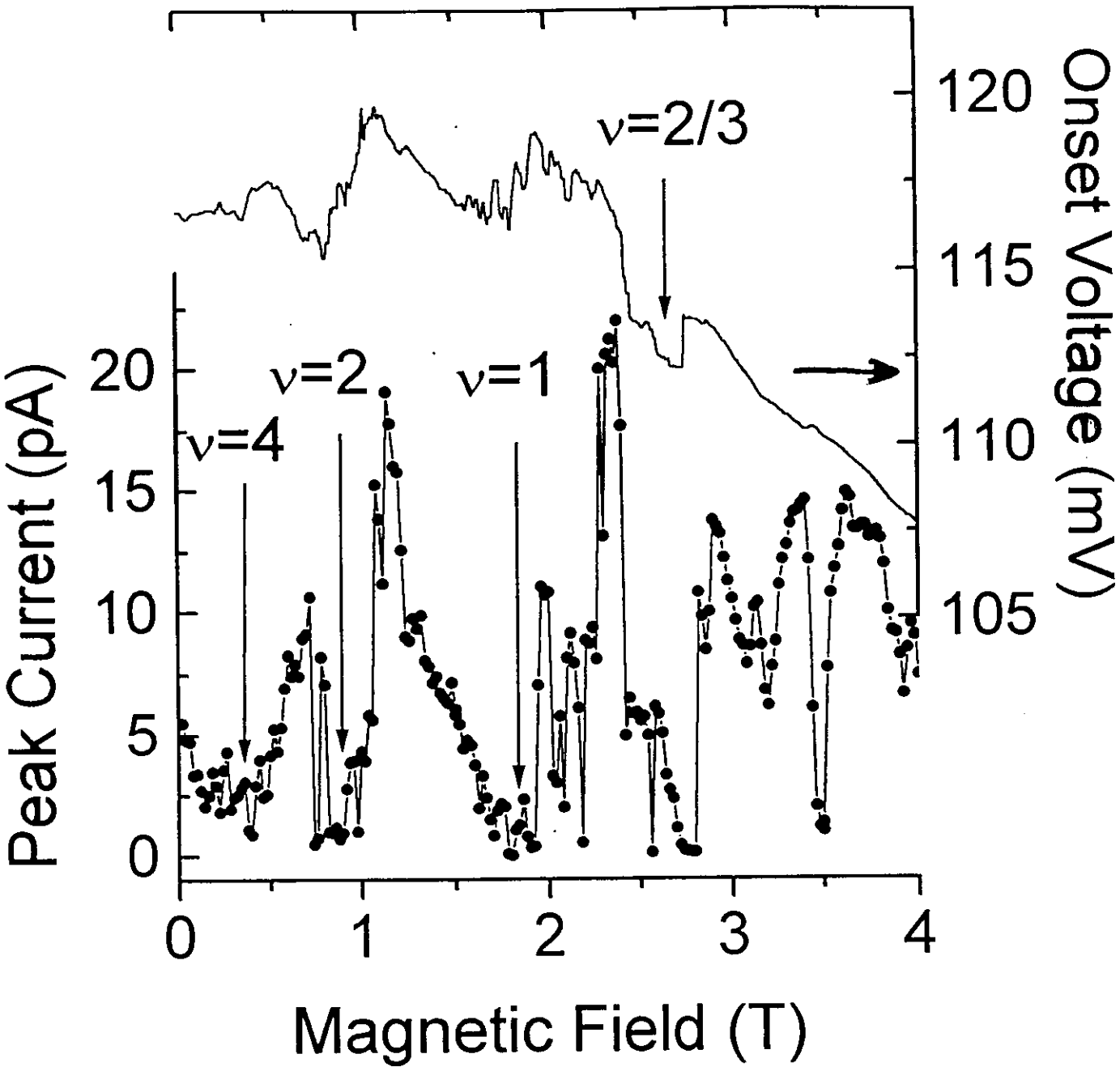
$\rho(\varepsilon_F)$ - Density of states at ε_F

ε_d - Dot energy

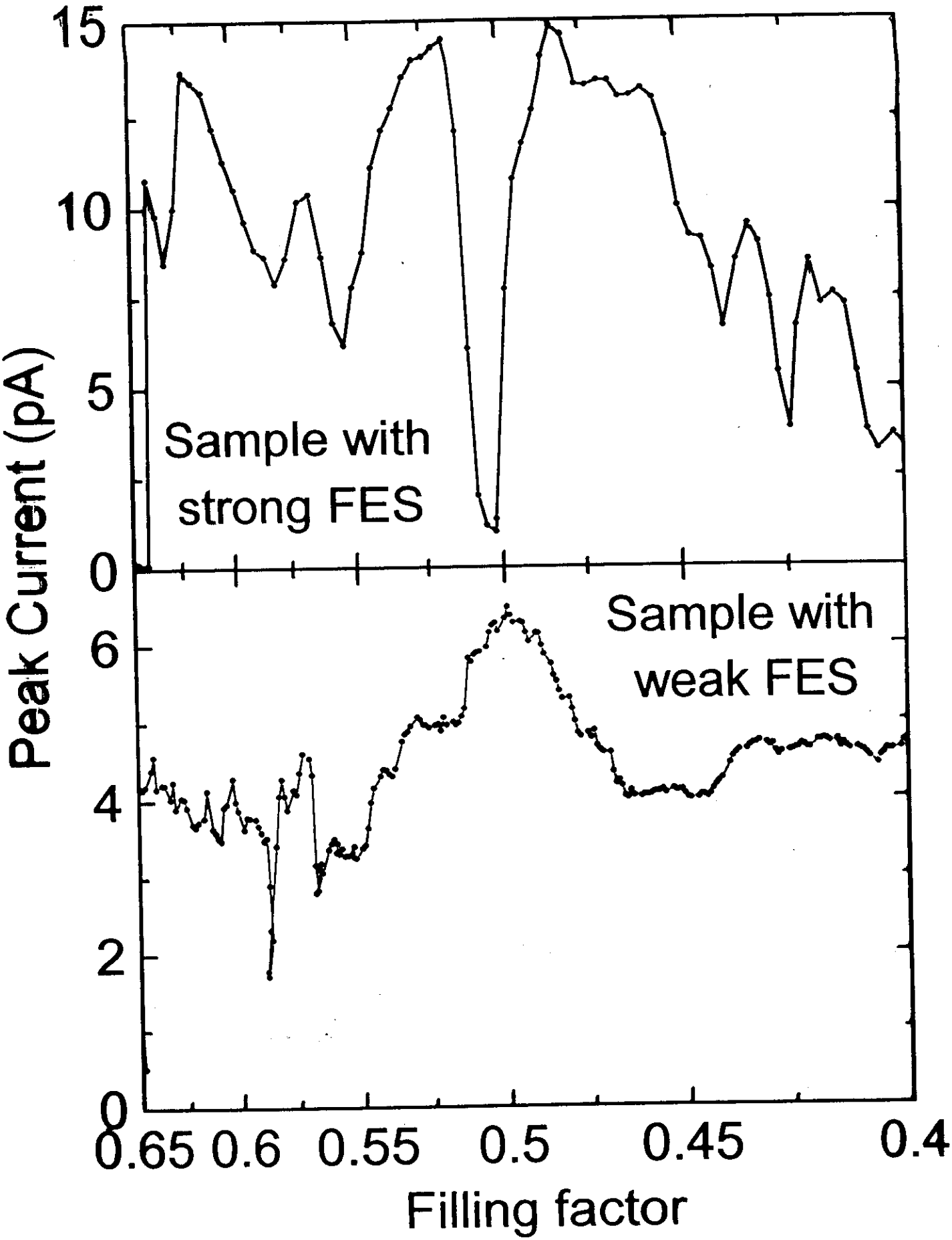
Ω - Area of 2DEG

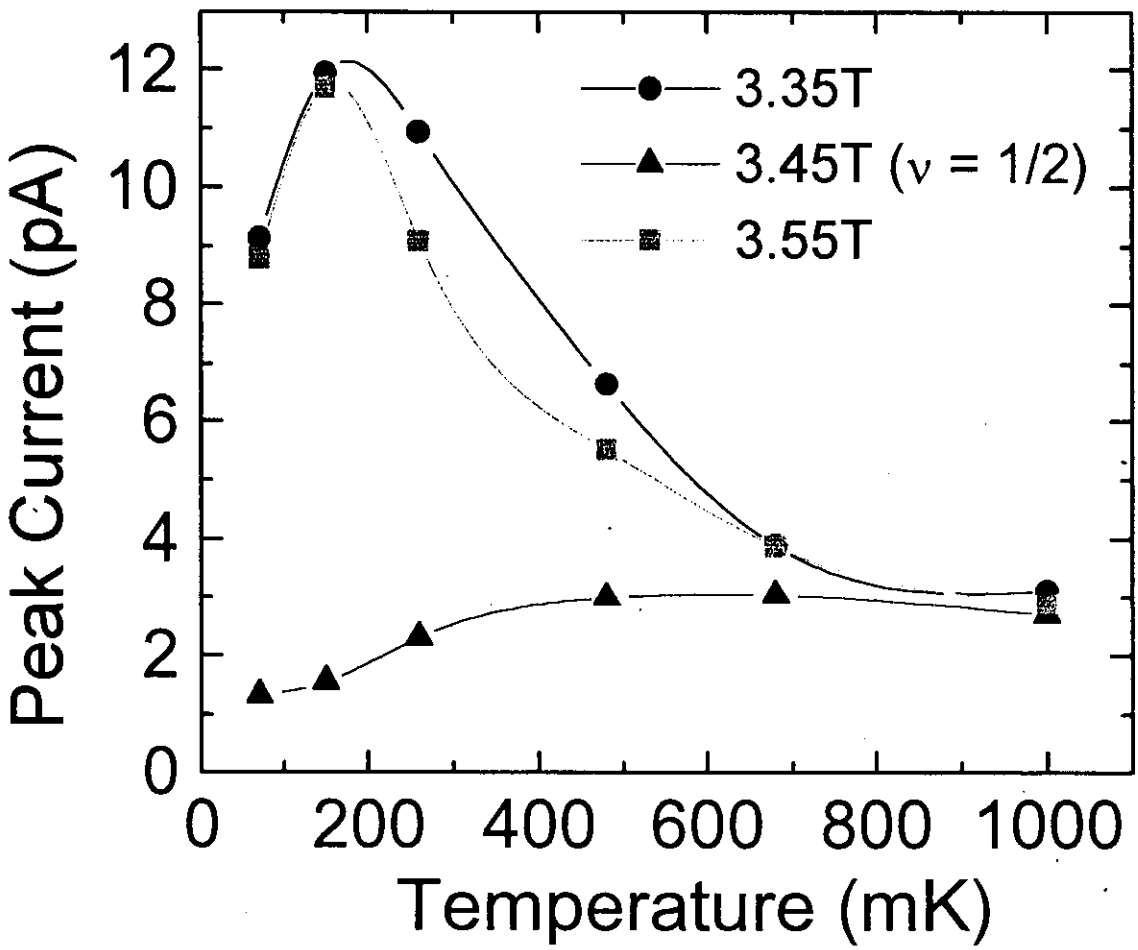
V_0 - Strength of interaction

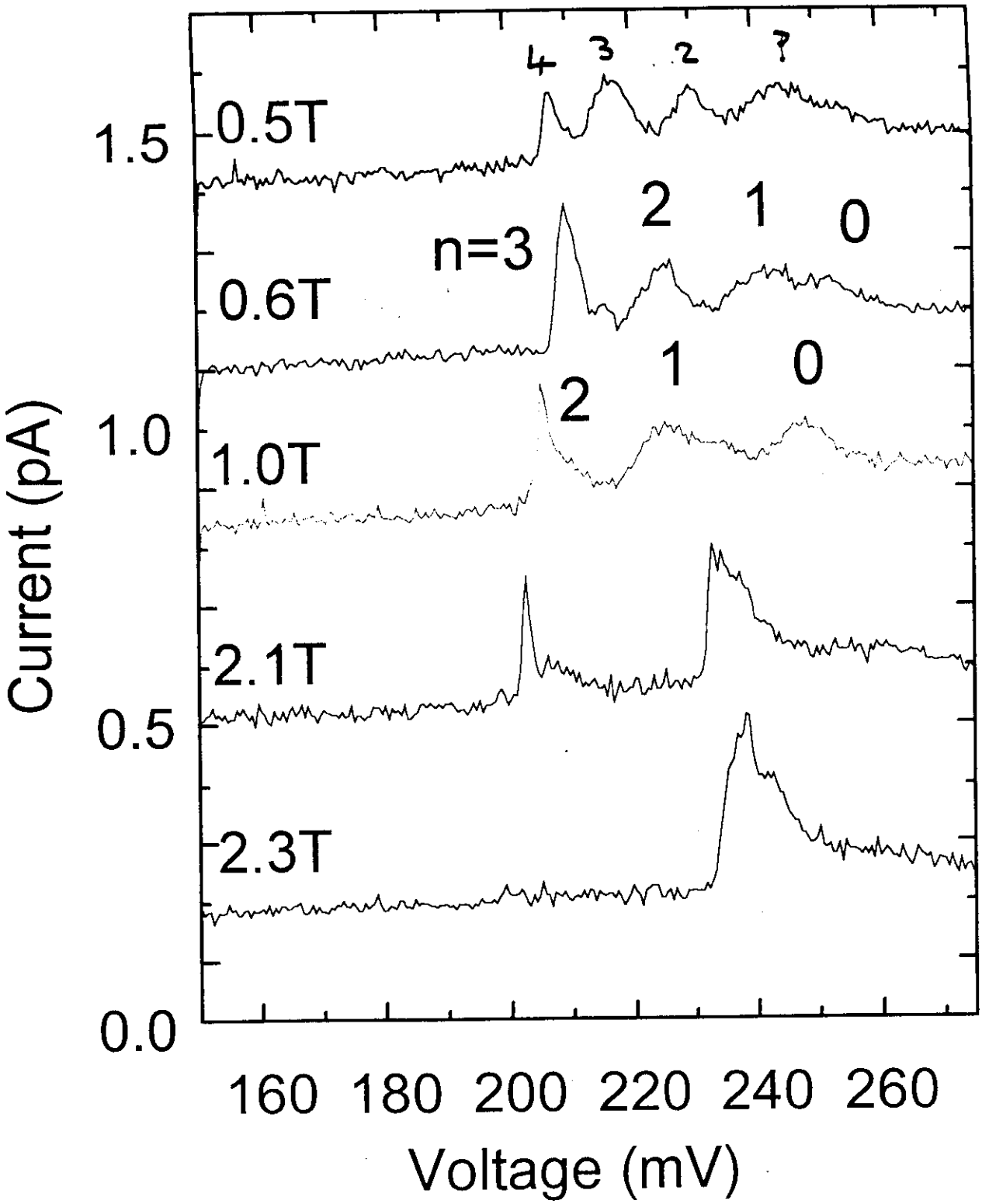
* V_0 depends on $\rho(\varepsilon_F)$ through screening
* When ε_F lies in region of high $\rho(\varepsilon_F)$ we get enhanced FES
* When ε_F lies in region of low $\rho(\varepsilon_F)$ we destroy FES

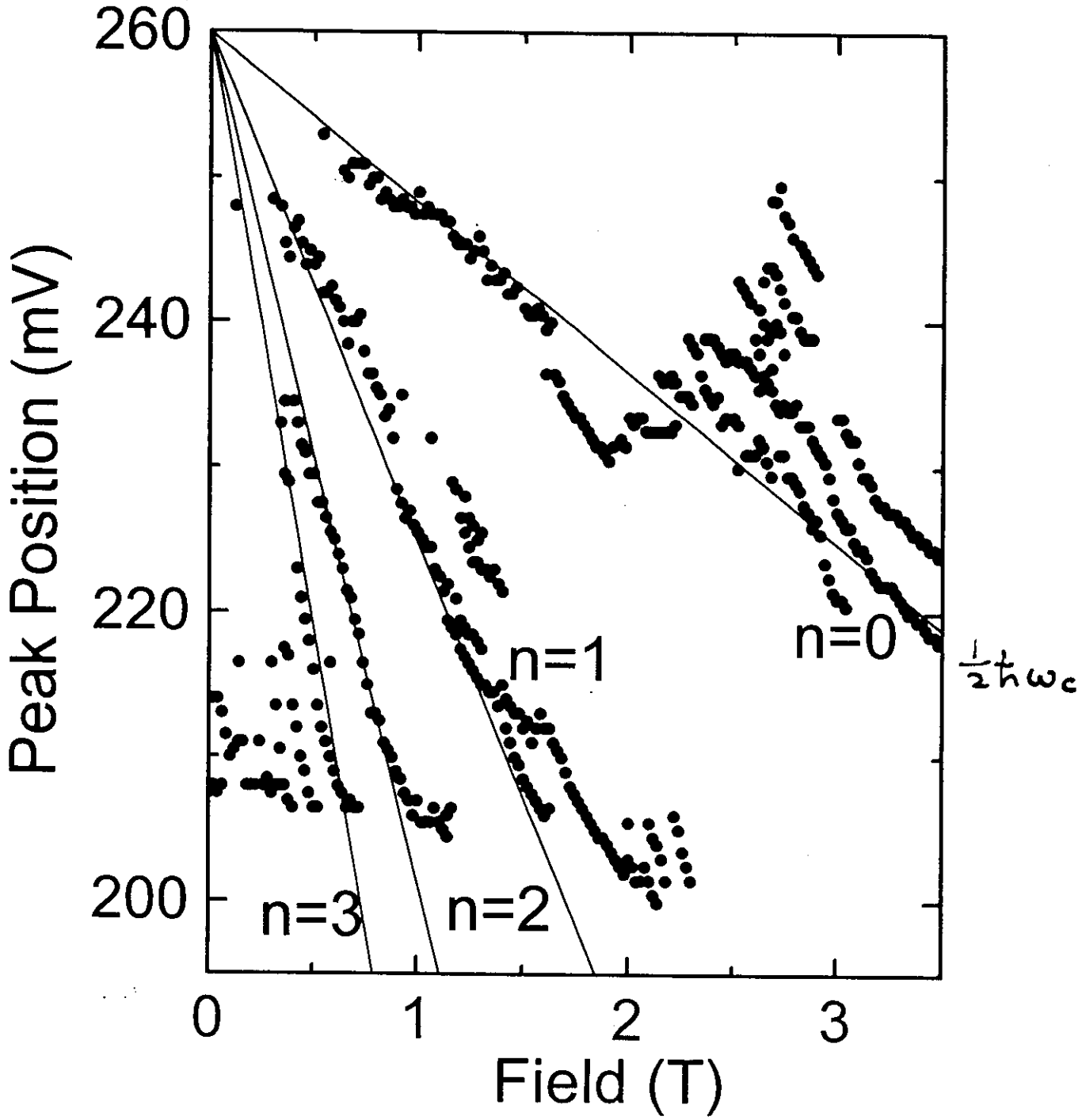


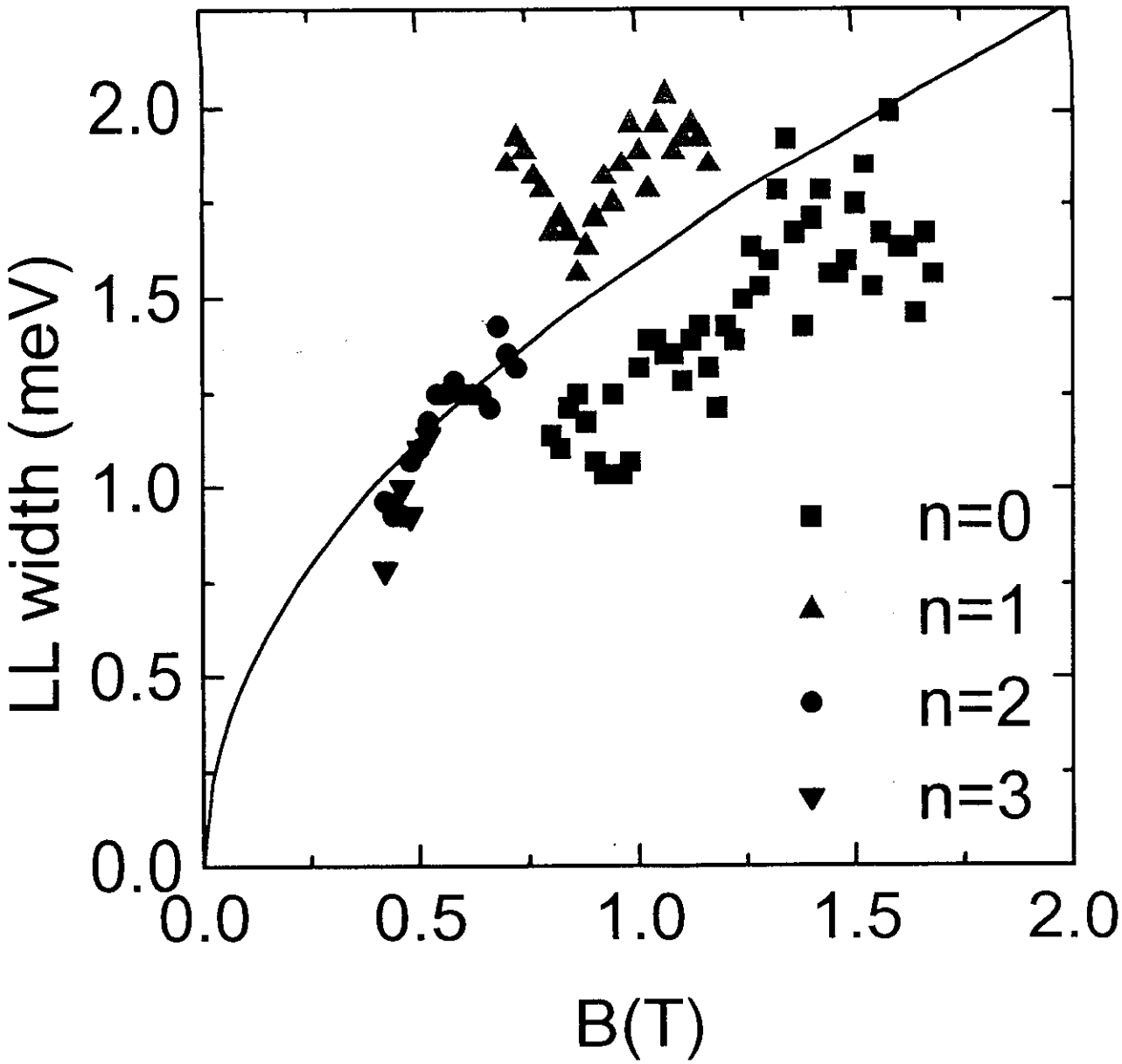
* NOTE THAT FES QUENCHES AT
  * $\nu = \frac{2}{3}$
  * $\nu = \frac{1}{2}$?


15
10
5
0
Sample with
strong FES
Sample with
weak FES
6
4
2
0
Peak Current (pA)
0.65
0.6
0.55
0.5
0.45
0.4
Filling factor


Peak Current (pA)
12
10
8
6
4
2
0
0
200
400
600
800
1000
Temperature (mK)
3.35T
3.45T (ν = 1/2)
3.55T


4
3
2
?
0.5T
1.5
2
1
0
n=3
0.6T
2
1
0
1.0T
1.0
2.1T
0.5
2.3T
0.0
Current (pA)
160
180
200
220
240
260
Voltage (mV)


260
240
220
200
Peak Position (mV)
0
1
2
3
Field (T)
n=0
n=1
n=2
n=3
$\frac{1}{2}\hbar\omega_c$

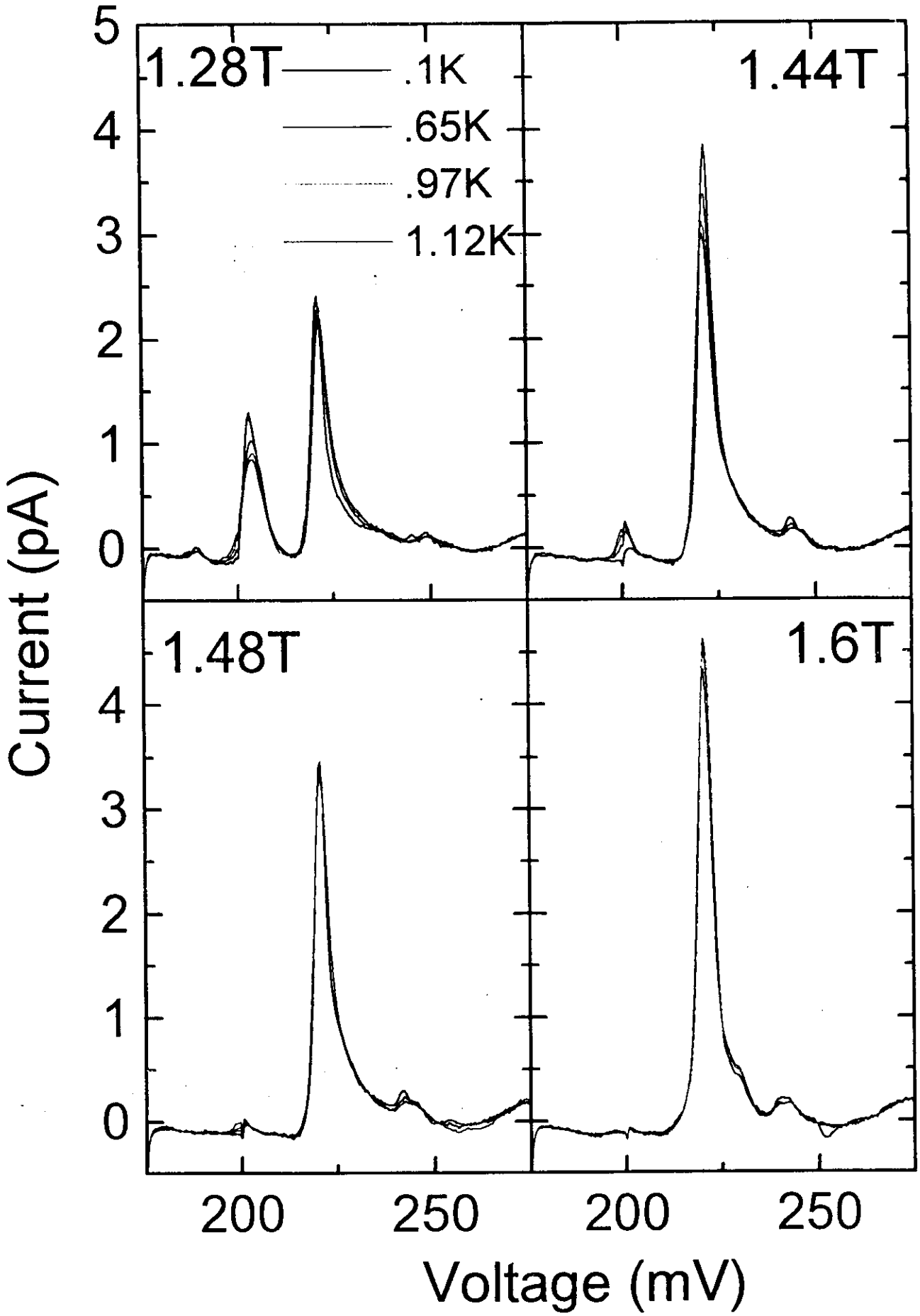


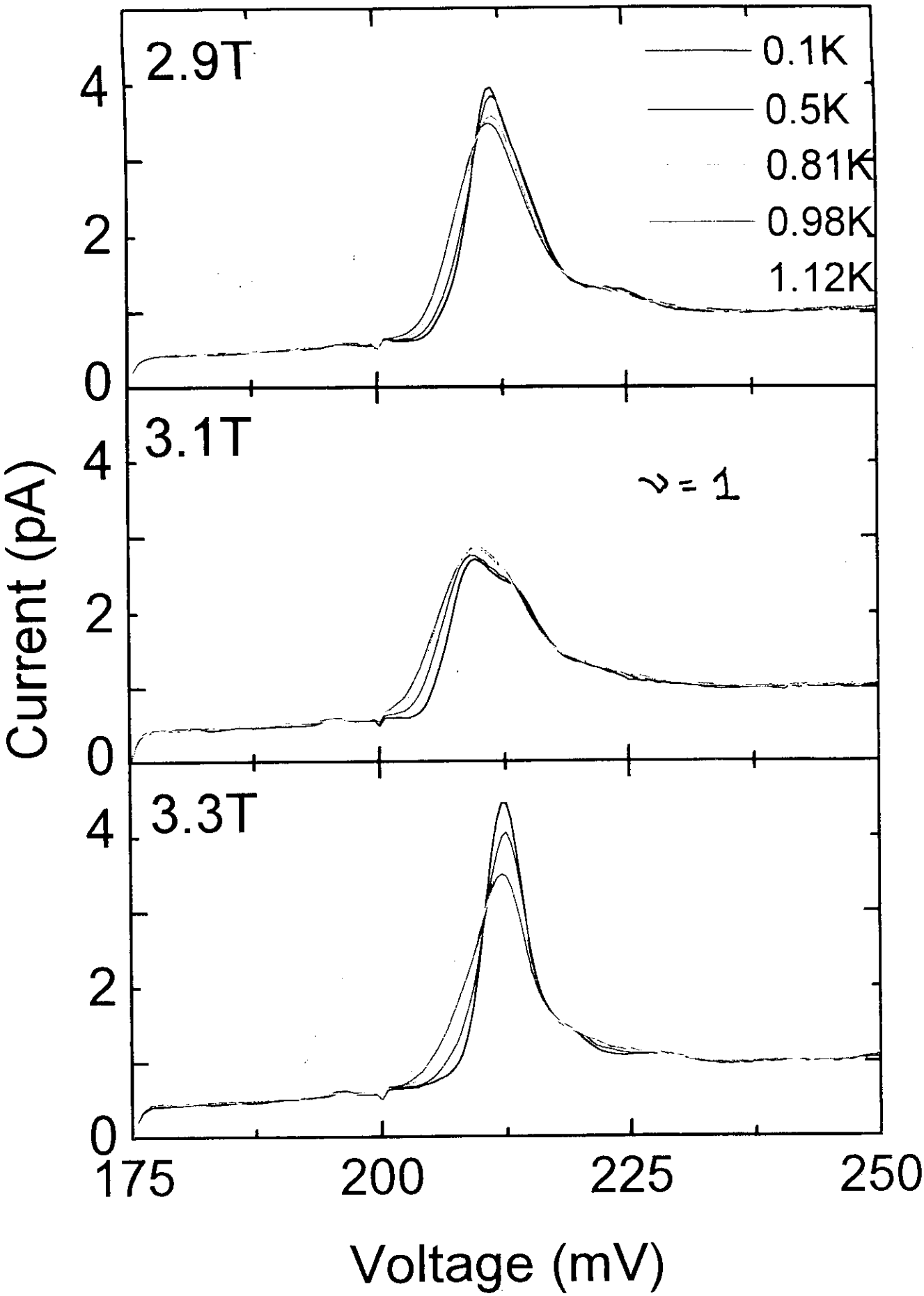
ANDO + UEMURA (1974)

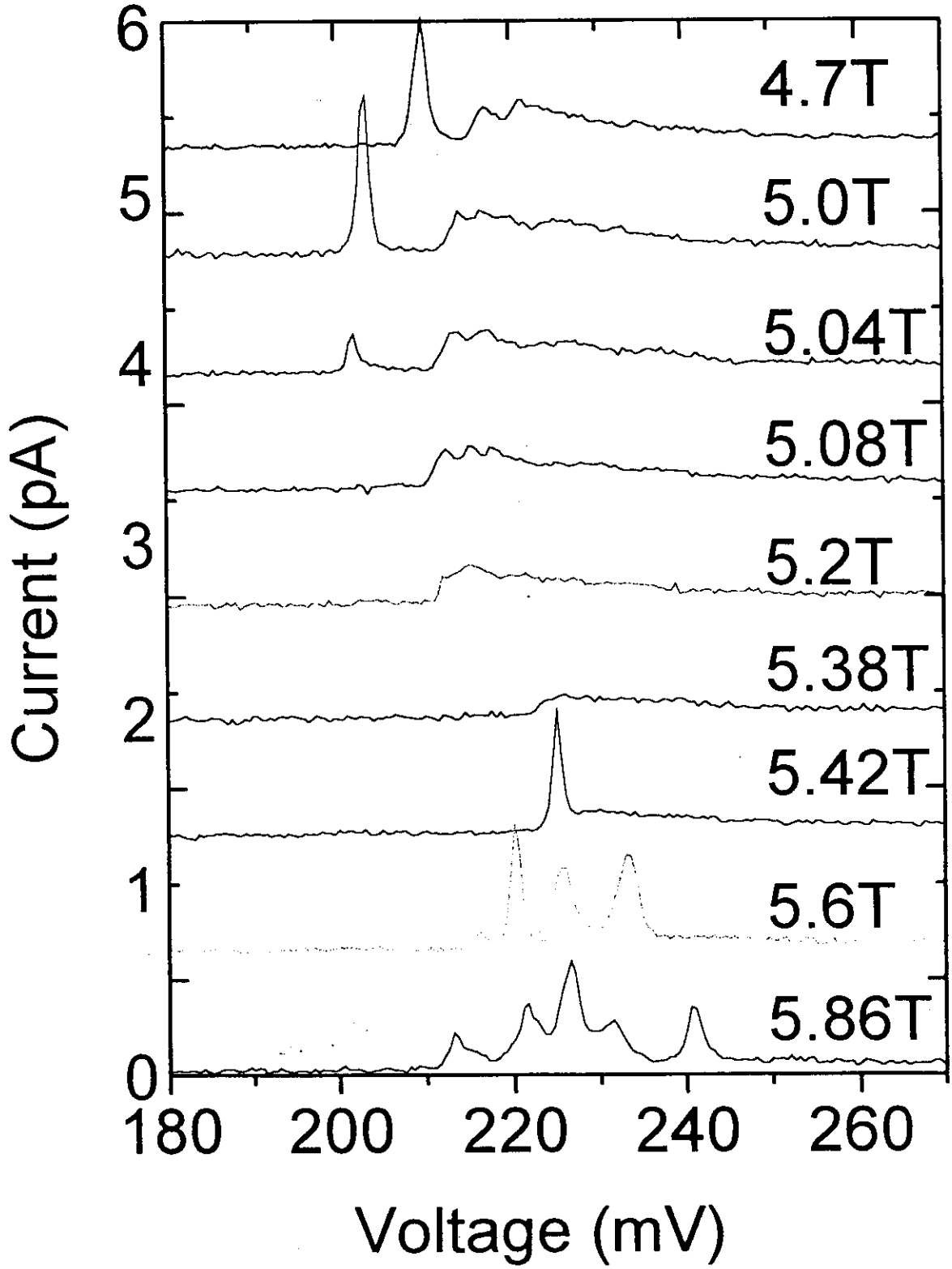
$$\Delta E \propto \left(\frac{B}{\mu}\right)^{\frac{1}{2}}$$

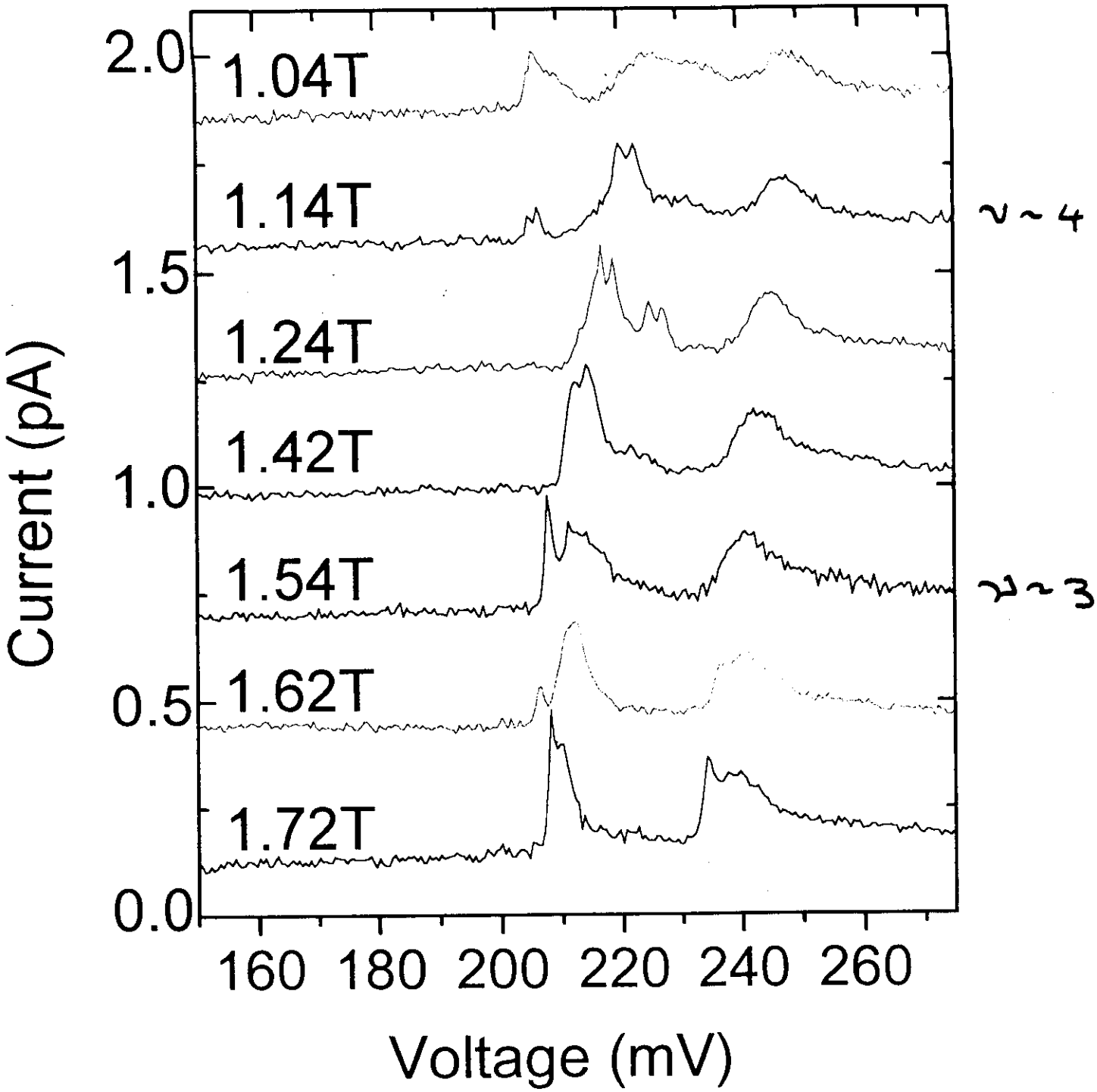
μ - mobility

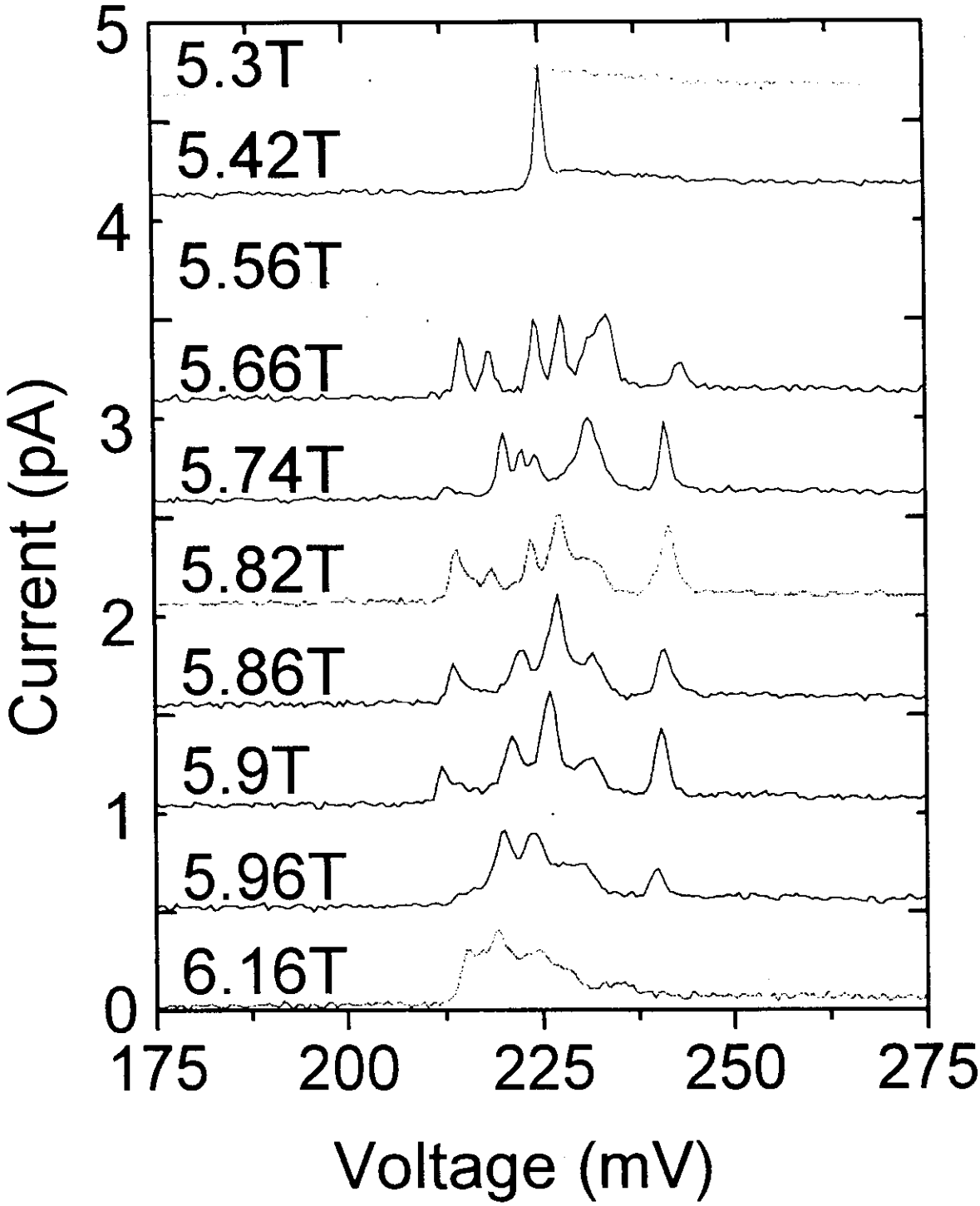
$\Rightarrow$ BEST LINE $\quad \mu \Rightarrow 0.7\ m^2 V^{-1} s^{-1}$

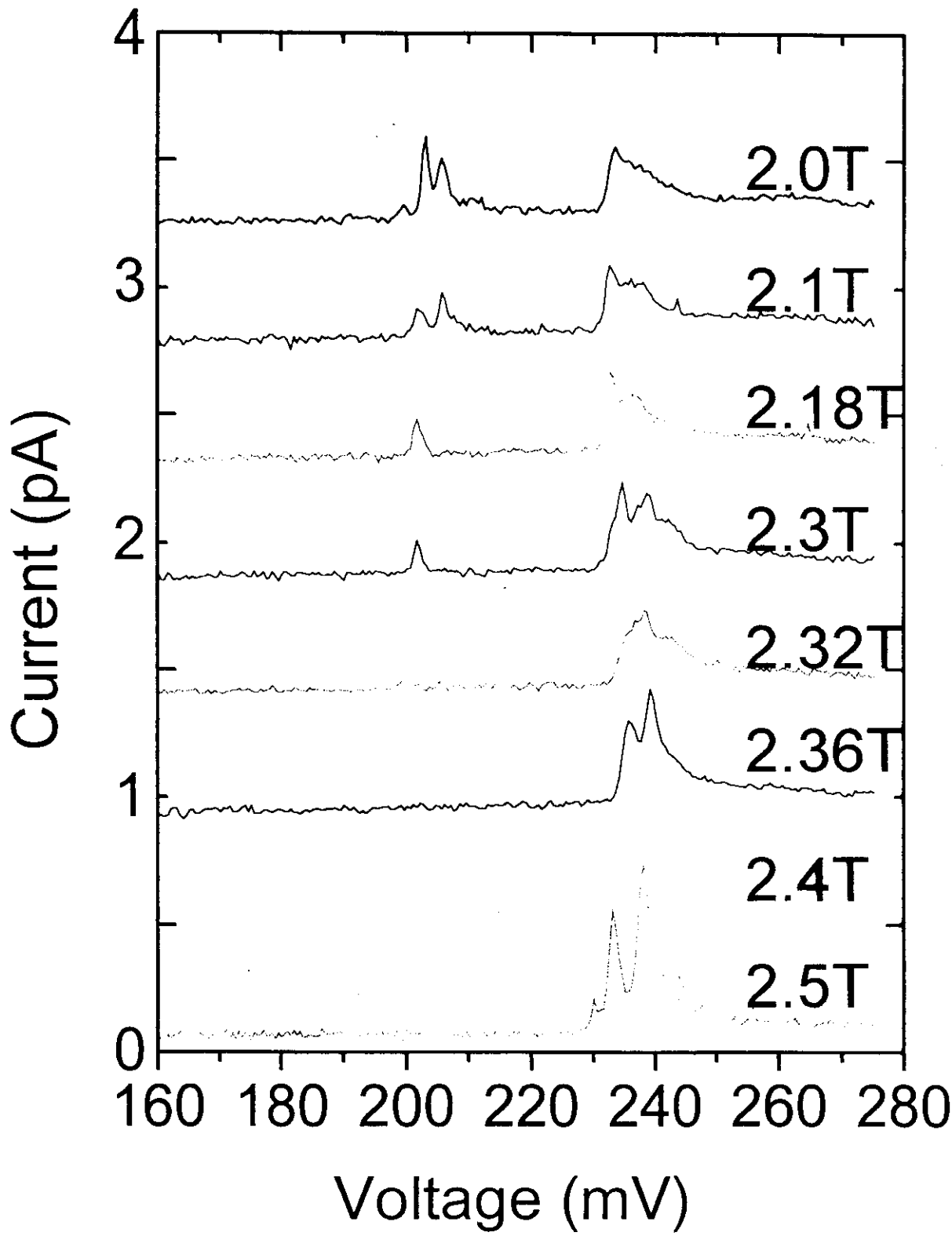

1.28T
.1K
.65K
.97K
1.12K
1.44T
1.48T
1.6T
Current (pA)
Voltage (mV)
0
1
2
3
4
5
200
250

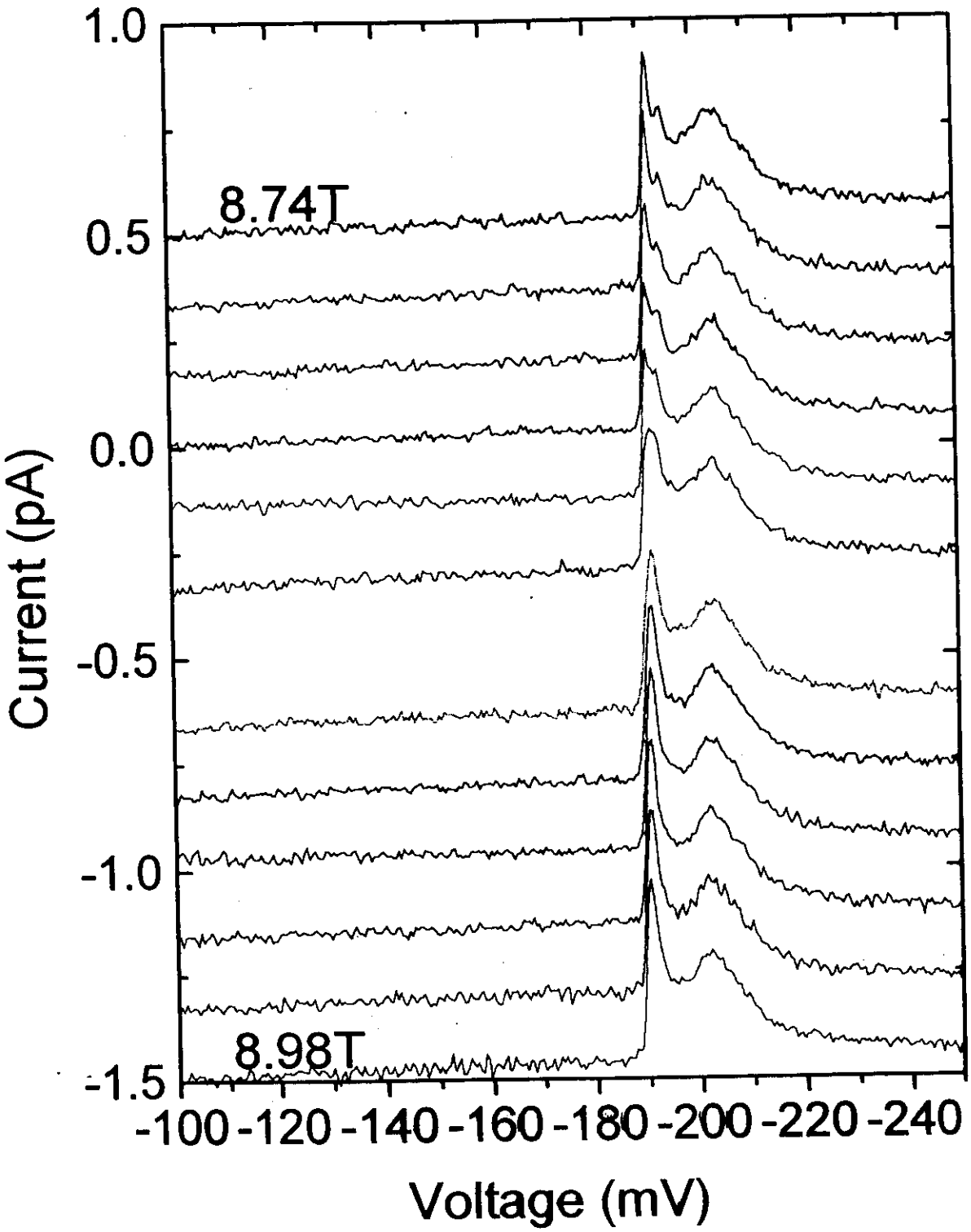

2.9T
0.1K
0.5K
0.81K
0.98K
1.12K
3.1T
ν = 1
3.3T
Current (pA)
Voltage (mV)
0
2
4
175
200
225
250


6
5
4
3
2
1
0
4.7T
5.0T
5.04T
5.08T
5.2T
5.38T
5.42T
5.6T
5.86T
Current (pA)
180
200
220
240
260
Voltage (mV)


2.0
1.5
1.0
0.5
0.0
1.04T
1.14T
1.24T
1.42T
1.54T
1.62T
1.72T
ν ~ 4
ν ~ 3
Current (pA)
160 180 200 220 240 260
Voltage (mV)


5.3T
5.42T
5.56T
5.66T
5.74T
5.82T
5.86T
5.9T
5.96T
6.16T
Current (pA)
Voltage (mV)
0
1
2
3
4
5
175
200
225
250
275


4
3
2
1
0
Current (pA)
2.0T
2.1T
2.18T
2.3T
2.32T
2.36T
2.4T
2.5T
160 180 200 220 240 260 280
Voltage (mV)


1.0
0.5
0.0
-0.5
-1.0
-1.5
8.74T
8.98T
Current (pA)
-100 -120 -140 -160 -180 -200 -220 -240
Voltage (mV)

CONCLUSIONS

* TUNNELLING THROUGH SINGLE QUANTUM DOT IS A LOCAL PROBE OF THE 2DEG

* CURRENT ONSET IS DOMINATED BY MANY-BODY EFFECTS

* MEASURE SPIN-SPLITTING OF DOT STATE

* MEASURE SPIN-SPLITTING OF 2DEG STATES

* MEASURE LANDAU LEVEL WIDTHS + SPIN GAPS DIRECTLY

* UNEXPLAINED EXOTIC EFFECTS