
Ames Research Center

1
00:00:00,633 --> 00:00:03,633
[music playing]

2
00:00:03,633 --> 00:00:06,633
[electrical sounds of data]

3
00:00:16,966 --> 00:00:23,233
- Welcome to the 2016
NASA Ames Summer Series.

4
00:00:23,233 --> 00:00:29,933
This year's Series
consists of 18 lectures

5
00:00:29,933 --> 00:00:34,300
from various experts
in different areas.

6
00:00:34,300 --> 00:00:37,733
Please join us
for the entire Series,

7
00:00:37,733 --> 00:00:43,066
not only for the ones
that seem interesting to you.

8
00:00:43,066 --> 00:00:46,900
You never know
what you may discover.

9
00:00:50,833 --> 00:00:53,866
Radiation tolerance
of electronics

10
00:00:53,866 --> 00:00:57,700
is critical for risk reduction
if we're going to go

11
00:00:57,700 --> 00:01:01,533

explore beyond
low Earth orbit.

12
00:01:01,533 --> 00:01:06,100
It is critical for the vehicles
that we will use and utilize

13
00:01:06,100 --> 00:01:10,833
as we go across,
exploring other planets.

14
00:01:12,166 --> 00:01:16,966
Vacuum electronics--
when you think of that term,

15
00:01:16,966 --> 00:01:20,566
you think back in history
to tubes

16
00:01:20,566 --> 00:01:23,966
and the old radio systems
that existed.

17
00:01:23,966 --> 00:01:28,233
But they also hold
the potential

18
00:01:28,233 --> 00:01:32,233
to have radiation immunity
for electronics.

19
00:01:32,233 --> 00:01:34,333
Today's seminar, entitled

20
00:01:34,333 --> 00:01:37,800
"Vacuum Electronics
in a Nanometer Era"

21
00:01:37,800 --> 00:01:43,100
will be given by

Dr. Jin-Woo Han.

22
00:01:43,100 --> 00:01:44,966
He received a BS in bio--

23
00:01:44,966 --> 00:01:47,933
in Information and
Communication Engineering

24
00:01:47,933 --> 00:01:52,333
from Inha University
in Korea,

25
00:01:52,333 --> 00:01:56,066
and an MS in
Electronic Engineering in 2006

26
00:01:56,066 --> 00:01:58,633
and a PhD in
Electrical Engineering from

27
00:01:58,633 --> 00:02:03,966
Korea Advanced Institute of
Science and Technology in 2010.

28
00:02:03,966 --> 00:02:06,733
Then he came and joined
Ames Research Center

29
00:02:06,733 --> 00:02:10,166
as a postdoc, and now he's
a research scientist

30
00:02:10,166 --> 00:02:13,400
with USRA at NASA Ames.

31
00:02:15,200 --> 00:02:17,600
He has many accomplishments

32

00:02:17,600 --> 00:02:20,666
in his early part
of his career so far,

33
00:02:20,666 --> 00:02:22,833
including the recent

34
00:02:22,833 --> 00:02:26,233
2016 Presidential
Early Career Award

35
00:02:26,233 --> 00:02:28,866
for Scientists and Engineers.

36
00:02:28,866 --> 00:02:33,433
Please join me in welcoming
Dr. Jin-Woo Han.

37
00:02:33,433 --> 00:02:36,433
[applause]

38
00:02:40,833 --> 00:02:43,466
- Thank you, Jacob,
for having me

39
00:02:43,466 --> 00:02:45,500
this opportunity...
[clears throat]

40
00:02:45,500 --> 00:02:49,233
to present
my project and work.

41
00:02:52,866 --> 00:02:57,600
So, today my talk is about
how the vacuum electronics play

42
00:02:57,600 --> 00:03:00,100
in a NASA mission,

43
00:03:00,100 --> 00:03:04,633
how it advanced, how it, like,
revolutionized the NASA mission.

44
00:03:04,633 --> 00:03:09,533
So, Jacob introduced very well,
but I want to repeat it again.

45
00:03:09,533 --> 00:03:13,366
In space, there is an abundance
of space radiation,

46
00:03:13,366 --> 00:03:15,100
including some x-ray, gamma ray,

47
00:03:15,100 --> 00:03:17,733
proton, neutron,
whatever you call it.

48
00:03:17,733 --> 00:03:20,366
We have to make
a space system

49
00:03:20,366 --> 00:03:23,900
that is highly intolerable
against--to

50
00:03:23,900 --> 00:03:26,600
the space radiation.

51
00:03:26,600 --> 00:03:28,533
And not only
for space radiation,

52
00:03:28,533 --> 00:03:32,933
there is a high temperature
found in the outer planet.

53
00:03:32,933 --> 00:03:35,733

So, in the case of Venus,
the Venus surface temperature

54
00:03:35,733 --> 00:03:39,333
can exceed as high as
500 degrees Celsius,

55
00:03:39,333 --> 00:03:41,933
which means that their
qualification has been

56
00:03:41,933 --> 00:03:44,733
treated differently
within Earth's application

57
00:03:44,733 --> 00:03:48,033
'cause no--
no electronics we have--

58
00:03:48,033 --> 00:03:51,666
we tested on the Earth's
application does not exceed.

59
00:03:51,666 --> 00:03:54,266
It does not exceed about
200 degrees Celsius,

60
00:03:54,266 --> 00:03:57,666
so we have to pay
a different attention

61
00:03:57,666 --> 00:04:00,533
for the reliability aspect.

62
00:04:00,533 --> 00:04:01,966
And not only for Venus.

63
00:04:01,966 --> 00:04:05,666
For example, if we do some
reentry of the--

64
00:04:05,666 --> 00:04:08,333
reentry in the descent
and landing application,

65
00:04:08,333 --> 00:04:11,300
the surface temperature
of the--the--

66
00:04:11,300 --> 00:04:13,900
the shuttle can exceed
about 1,000 degrees Celsius

67
00:04:13,900 --> 00:04:17,300
while we want to monitor
what is happening

68
00:04:17,300 --> 00:04:18,866
during the reentry period.

69
00:04:18,866 --> 00:04:21,666
So, for that perspective,
we also deal with

70
00:04:21,666 --> 00:04:24,566
some electronics that can work

71
00:04:24,566 --> 00:04:28,500
as high as
1,000 degrees Celsius.

72
00:04:28,500 --> 00:04:33,400
So, here is an example of what--
example of the failure

73
00:04:33,400 --> 00:04:35,900
or the error found
in the NASA mission

74

00:04:35,900 --> 00:04:38,900
across the different
spacecrafts.

75
00:04:38,900 --> 00:04:41,566
Upon the space radiation,
there is a,

76
00:04:41,566 --> 00:04:44,900
like, a humongous different type
of errors were found

77
00:04:44,900 --> 00:04:48,633
in our previous mission,

78
00:04:48,633 --> 00:04:52,566
which includes some big error,

79
00:04:52,566 --> 00:04:56,466
something like some
power failure,

80
00:04:56,466 --> 00:04:58,266
some upset of electronics.

81
00:04:58,266 --> 00:05:00,333
So, this is just an example,

82
00:05:00,333 --> 00:05:03,333
so it means that we need to,
I mean, find a way

83
00:05:03,333 --> 00:05:06,766
how to deal with,
how to minimize the risk

84
00:05:06,766 --> 00:05:09,566
upon the space radiation.

85

00:05:09,566 --> 00:05:13,000
So, here's my contents
of today's talk.

86
00:05:13,000 --> 00:05:14,600
Then I will go further.

87
00:05:14,600 --> 00:05:19,300
So, what I'm trying to say,
talk today, is...

88
00:05:19,300 --> 00:05:22,933
very relevant to the fundamental
building block of electronics.

89
00:05:22,933 --> 00:05:25,966
This is the example
of how we want to explain

90
00:05:25,966 --> 00:05:29,133
the cause of the failure
in space electronics.

91
00:05:29,133 --> 00:05:34,433
There's the "Curiosity,"
this is a system, the rover,

92
00:05:34,433 --> 00:05:38,600
but every system contains
printed circuit board

93
00:05:38,600 --> 00:05:43,366
which contains the population
of electronic device,

94
00:05:43,366 --> 00:05:46,866
which is called an IC--
integrated circuit.

95
00:05:46,866 --> 00:05:49,033

Then within
the integrated circuit,

96
00:05:49,033 --> 00:05:51,000
there is a fundamental
building block,

97
00:05:51,000 --> 00:05:53,233
which is called a transistor.

98
00:05:53,233 --> 00:05:57,233
And then billions
of transistors are combined

99
00:05:57,233 --> 00:06:00,366
and they're placed in a rocket,
as if we build up a Lego,

100
00:06:00,366 --> 00:06:03,300
it functions as
a single-functioning chip.

101
00:06:03,300 --> 00:06:07,666
So, the failure mechanism
of the electronics

102
00:06:07,666 --> 00:06:10,800
is very relevant
to the failure mechanism

103
00:06:10,800 --> 00:06:14,700
found in--within a transistor.

104
00:06:14,700 --> 00:06:19,333
As you see in the left,
the lower figures.

105
00:06:19,333 --> 00:06:23,066
And here is a schematic view
that I will explain,

106
00:06:23,066 --> 00:06:25,900
a glossary of the transistor.

107
00:06:25,900 --> 00:06:28,300
So, transistor is basically
made out of

108
00:06:28,300 --> 00:06:30,166
the semiconductor materials.

109
00:06:30,166 --> 00:06:34,166
And then we place, which is
called source and drain,

110
00:06:34,166 --> 00:06:37,900
and the resistance across
the source and drain

111
00:06:37,900 --> 00:06:40,000
is controlled by
the third terminal,

112
00:06:40,000 --> 00:06:41,366
which is called a gate.

113
00:06:41,366 --> 00:06:43,933
And between the gate
and the channel,

114
00:06:43,933 --> 00:06:48,900
there is an insulator
that is designed to--

115
00:06:48,900 --> 00:06:51,433
designed to deliver
electrostatic field,

116
00:06:51,433 --> 00:06:54,000

but preventing
the electric current

117
00:06:54,000 --> 00:06:55,733
leaking through the gate.

118
00:06:55,733 --> 00:06:57,700
And then around
the single transistor,

119
00:06:57,700 --> 00:07:01,800
the transistor is isolated
by the insulator.

120
00:07:01,800 --> 00:07:04,933
So, this is the fundamental
structure of the device.

121
00:07:04,933 --> 00:07:09,566
And then what I want to focus
is all the material

122
00:07:09,566 --> 00:07:13,066
is consisting
of three basic blocks,

123
00:07:13,066 --> 00:07:18,100
which is an insulator,
and metal, and semiconductor.

124
00:07:18,100 --> 00:07:23,266
And then what is happening
in the material is this.

125
00:07:23,266 --> 00:07:25,633
So, this is an example of atoms,

126
00:07:25,633 --> 00:07:29,366
which becomes a fundamental,
I mean, species

127
00:07:29,366 --> 00:07:32,033
consisting every element
of the material.

128
00:07:32,033 --> 00:07:36,633
So, when high energetic
particles are heating the atoms,

129
00:07:36,633 --> 00:07:40,266
and then this,
the momentum transfers from

130
00:07:40,266 --> 00:07:44,166
the energetic radiation
into the atoms,

131
00:07:44,166 --> 00:07:47,866
it actually knock off
the outer-bounded electron,

132
00:07:47,866 --> 00:07:52,800
then makes the atoms ion,
and it leaves free electrons.

133
00:07:52,800 --> 00:07:55,833
And these free electrons become
freely moving

134
00:07:55,833 --> 00:07:57,266
across the electric field.

135
00:07:57,266 --> 00:08:00,100
So, this is the how--

136
00:08:00,100 --> 00:08:05,666
how it cause a failure
in semiconductor system.

137

```
00:08:05,666 --> 00:08:08,633
So, as I explained,
there is three materials.

138
00:08:08,633 --> 00:08:13,166
One is metal conductor, and
semiconductor, and insulator.

139
00:08:13,166 --> 00:08:15,466
The material guys,
or the device physics guy

140
00:08:15,466 --> 00:08:17,900
use a term called
an "energy gap."

141
00:08:17,900 --> 00:08:20,733
So, I don't want
to go in detail,

142
00:08:20,733 --> 00:08:23,166
but in conductor,
there's already

143
00:08:23,166 --> 00:08:26,900
a humongous amount
of free electrons there.

144
00:08:26,900 --> 00:08:31,133
So, the energetic space
particles hit the conductor,

145
00:08:31,133 --> 00:08:35,000
it may create
extra electrons,

146
00:08:35,000 --> 00:08:37,466
but it doesn't do much
because there's already

147
```

00:08:37,466 --> 00:08:39,333
free electrons there.

148
00:08:39,333 --> 00:08:42,633
But in semiconductor,
their density of free electrons

149
00:08:42,633 --> 00:08:46,333
can be modulated upon
the voltage applied across it.

150
00:08:46,333 --> 00:08:49,833
So, it can be either
insulating property

151
00:08:49,833 --> 00:08:51,366
or the conducting property,

152
00:08:51,366 --> 00:08:53,266
depending on what voltage
you're applying it.

153
00:08:53,266 --> 00:08:56,033
But when space radiation

154
00:08:56,033 --> 00:08:58,000
penetrates through
the semiconductor,

155
00:08:58,000 --> 00:08:59,900
it creates free electrons.

156
00:08:59,900 --> 00:09:04,033
Then, in case the
semiconductor's supposed to be

157
00:09:04,033 --> 00:09:08,233
a insulator,
but the ionizing--

158
00:09:08,233 --> 00:09:11,366
ionized electron
due to space radiation,

159
00:09:11,366 --> 00:09:15,866
it acts as if the semiconductor
is a metal conductor.

160
00:09:15,866 --> 00:09:19,433
So, it causes a malfunction
of the transistor.

161
00:09:19,433 --> 00:09:21,000
So, this is one aspect.

162
00:09:21,000 --> 00:09:24,000
And then the insulator,
insulator--

163
00:09:24,000 --> 00:09:25,566
even though the insulator--

164
00:09:25,566 --> 00:09:28,466
the band gap of insulator
is too wide,

165
00:09:28,466 --> 00:09:31,300
so even though we apply
high potential

166
00:09:31,300 --> 00:09:34,600
it never turned into
the semiconducting properties.

167
00:09:34,600 --> 00:09:38,500
But when the radiation
hits the insulator,

168
00:09:38,500 --> 00:09:42,466

it creates a ionization,

169
00:09:42,466 --> 00:09:46,533
but these ionized electrons
is not like a free elect--

170
00:09:46,533 --> 00:09:48,700
free carriers
but it's localized

171
00:09:48,700 --> 00:09:52,400
and it acts as a defect
within the insulator.

172
00:09:52,400 --> 00:09:56,266
So, the basic difference
between semiconductor

173
00:09:56,266 --> 00:09:59,033
and insulator
is that in semiconductor,

174
00:09:59,033 --> 00:10:02,800
it is, like, spontaneous
and it's momentarily.

175
00:10:02,800 --> 00:10:04,633
So, it means that,
as time goes by,

176
00:10:04,633 --> 00:10:06,833
the free electrons
really combine back

177
00:10:06,833 --> 00:10:09,433
and then it turns back
into original states.

178
00:10:09,433 --> 00:10:13,266
So, it's like a soft-error

but in the insulator.

179
00:10:13,266 --> 00:10:16,566
Once it ionize it,
and then it become localized

180
00:10:16,566 --> 00:10:20,233
and fixed it,
so it's cumulative.

181
00:10:20,233 --> 00:10:22,200
And it ages as time goes by.

182
00:10:22,200 --> 00:10:26,266
So we can, like, discriminate
the soft-error

183
00:10:26,266 --> 00:10:30,166
and hard-error,
which is aging,

184
00:10:30,166 --> 00:10:34,433
which we--what we call it as our
"total ionizing dose,"

185
00:10:34,433 --> 00:10:38,000
TID, in short.

186
00:10:38,000 --> 00:10:39,466
So, there are three types
of error.

187
00:10:39,466 --> 00:10:41,900
Some soft-error, instantaneous,

188
00:10:41,900 --> 00:10:43,900
which is relevant
to semiconductor.

189

00:10:43,900 --> 00:10:46,400
And then the kind
that is cumulative.

190
00:10:46,400 --> 00:10:51,033
It is aging
relevant to the oxide,

191
00:10:51,033 --> 00:10:53,133
which has a higher band gap.

192
00:10:53,133 --> 00:10:55,333
So, this is a schematic view.

193
00:10:55,333 --> 00:10:58,200
When the energetic particles
are penetrating

194
00:10:58,200 --> 00:11:01,066
through this
semiconductor region,

195
00:11:01,066 --> 00:11:03,300
and then the heavy iron
has a higher mass,

196
00:11:03,300 --> 00:11:05,200
so it penetrates
all the way through

197
00:11:05,200 --> 00:11:07,200
from the surface of the silicon

198
00:11:07,200 --> 00:11:09,800
into the bottom surface
of the silicon.

199
00:11:09,800 --> 00:11:13,333
And then it creates
the charging funnel,

200
00:11:13,333 --> 00:11:17,100
but for the proton,
which has relatively lower mass.

201
00:11:17,100 --> 00:11:19,933
And then it creates
just a single pair

202
00:11:19,933 --> 00:11:24,766
that can pair as an extra.

203
00:11:24,766 --> 00:11:28,266
So, what happened in reality is,

204
00:11:28,266 --> 00:11:30,500
when we build a circuit,

205
00:11:30,500 --> 00:11:34,400
we build a circuit by using
two different polarities

206
00:11:34,400 --> 00:11:35,433
of a transistor.

207
00:11:35,433 --> 00:11:37,566
One is called a N-type
transistor.

208
00:11:37,566 --> 00:11:40,533
And the other called
P-type transistor.

209
00:11:40,533 --> 00:11:43,666
But when the N-type transistor
and P-type transistor

210
00:11:43,666 --> 00:11:46,666
are placed side by side

211
00:11:46,666 --> 00:11:48,766
to result in
a certain function,

212
00:11:48,766 --> 00:11:51,200
this is called, like,
a inverse function.

213
00:11:51,200 --> 00:11:53,266
This is a very basic
building block

214
00:11:53,266 --> 00:11:55,700
of the logic circuit.

215
00:11:55,700 --> 00:11:57,366
Then, there in the bottom side,

216
00:11:57,366 --> 00:12:00,100
the bulk region of the device,

217
00:12:00,100 --> 00:12:02,766
it creates
a parasitic transistor path,

218
00:12:02,766 --> 00:12:05,733
which is supposed to be
always off.

219
00:12:05,733 --> 00:12:09,200
But this parasitic transistor,
which is, like,

220
00:12:09,200 --> 00:12:14,033
denoted in line, figure--
in this bigger graph,

221
00:12:14,033 --> 00:12:18,866

it is initiated
once it is triggered

222
00:12:18,866 --> 00:12:21,966
by the radiation ionization.

223
00:12:21,966 --> 00:12:24,666
So, the device is supposed
to be always off,

224
00:12:24,666 --> 00:12:28,100
the parasitic feedback loop
is supposed to be always off,

225
00:12:28,100 --> 00:12:33,033
but when space radiation
initializes the creation

226
00:12:33,033 --> 00:12:37,466
of electron-hole pairs
then it initiates

227
00:12:37,466 --> 00:12:39,566
the feedback loop

228
00:12:39,566 --> 00:12:42,266
and it becomes
always-on state.

229
00:12:42,266 --> 00:12:47,233
So, it is one of the causes
of soft-error.

230
00:12:47,233 --> 00:12:49,733
And then the other one is
what I call

231
00:12:49,733 --> 00:12:50,866
a cumulative errors.

232
00:12:50,866 --> 00:12:54,700
And this cumulative error
is related to

233
00:12:54,700 --> 00:13:00,700
the insulating region
around the channel.

234
00:13:00,700 --> 00:13:05,033
And then, as I explained,
this is localized and fixed

235
00:13:05,033 --> 00:13:06,866
and it's cumulative.

236
00:13:06,866 --> 00:13:12,200
So, these fixed charges
acts as a pseudo-gate

237
00:13:12,200 --> 00:13:14,166
formed in the side wall
of the channel.

238
00:13:14,166 --> 00:13:18,266
So, the role
of the insulating region

239
00:13:18,266 --> 00:13:21,833
is just isolate the one device
to adjust the device.

240
00:13:21,833 --> 00:13:23,400
But as time goes by,

241
00:13:23,400 --> 00:13:26,100
as it contains
the localized charges,

242
00:13:26,100 --> 00:13:30,066

these charges form
a parasitic transistor path

243
00:13:30,066 --> 00:13:32,900
on its side wall
of the channel.

244
00:13:32,900 --> 00:13:35,300
So, it quickly turns on
the device.

245
00:13:35,300 --> 00:13:39,766
And the other insulator
found in a transistor

246
00:13:39,766 --> 00:13:42,333
is gate insulating oxide,

247
00:13:42,333 --> 00:13:45,466
which is on the right
and top portion.

248
00:13:45,466 --> 00:13:47,833
Even though the thickness
is very thin,

249
00:13:47,833 --> 00:13:51,366
it is also an insulator,
so it contains--

250
00:13:51,366 --> 00:13:53,600
it can contain fixed charges.

251
00:13:53,600 --> 00:13:57,666
These fixed charges used
to degrade the drive current

252
00:13:57,666 --> 00:14:00,266
of a transistor
and increase the--

253
00:14:00,266 --> 00:14:02,366
the leakage current
of a transistor.

254
00:14:02,366 --> 00:14:04,966
So, this shifts
device parameter,

255
00:14:04,966 --> 00:14:07,000
like some drive current

256
00:14:07,000 --> 00:14:09,033
and off-state leakage current
vessel voltage

257
00:14:09,033 --> 00:14:12,900
and then slope of
the transistor IV curve.

258
00:14:12,900 --> 00:14:15,833
So, how we countermeasure

259
00:14:15,833 --> 00:14:20,233
these radiation effects is this.

260
00:14:20,233 --> 00:14:22,466
This is, like,
too many approaches,

261
00:14:22,466 --> 00:14:26,833
but to make it short,
the most straightforward way

262
00:14:26,833 --> 00:14:31,566
to mitigate space radiation is
shielding the entire electronics

263
00:14:31,566 --> 00:14:34,200

with a very thick box
of the metal

264
00:14:34,200 --> 00:14:38,666
then the metal shield can absorb
the space radiation.

265
00:14:38,666 --> 00:14:42,533
For that way, the space
radiation doesn't reach

266
00:14:42,533 --> 00:14:44,900
into the device.

267
00:14:44,900 --> 00:14:49,633
But as a NASA mission,
we are all focused

268
00:14:49,633 --> 00:14:51,000
on the mass, or the payload,

269
00:14:51,000 --> 00:14:53,566
'cause every pound
we want to lift

270
00:14:53,566 --> 00:14:56,333
into the low Earth's orbit,
it costs.

271
00:14:56,333 --> 00:14:59,033
The weight translates
into cost, right?

272
00:14:59,033 --> 00:15:03,900
Then, if we--actually,
we want to save this cost.

273
00:15:05,900 --> 00:15:10,000
So, I was thinking that,
what if we make a device

274
00:15:10,000 --> 00:15:13,400
which is intrinsically
resistant,

275
00:15:13,400 --> 00:15:16,000
immune against
the space radiation?

276
00:15:16,000 --> 00:15:18,433
So, that was my starting point.

277
00:15:18,433 --> 00:15:21,466
So, this is a brief history
of how the electron--

278
00:15:21,466 --> 00:15:23,233
I mean, space electron society

279
00:15:23,233 --> 00:15:26,033
have evolved
the device structure.

280
00:15:26,033 --> 00:15:28,233
So, see on the very left

281
00:15:28,233 --> 00:15:30,333
is very early stage
device structures,

282
00:15:30,333 --> 00:15:34,766
which has become, actually,
our standard process.

283
00:15:34,766 --> 00:15:37,900
But, as you see,
the side wall of a transistor

284
00:15:37,900 --> 00:15:40,333

is interfacing
with the materials

285
00:15:40,333 --> 00:15:42,800
that cause a parasitic path,

286
00:15:42,800 --> 00:15:44,633
parasitic, leakage path
of a transistor.

287
00:15:44,633 --> 00:15:47,033
So, the people
were thinking that

288
00:15:47,033 --> 00:15:50,666
we need to minimize
the contacting area

289
00:15:50,666 --> 00:15:52,766
between
the semiconductor channel

290
00:15:52,766 --> 00:15:54,966
and insulating region.

291
00:15:54,966 --> 00:15:59,766
So, the second generation
is making a device

292
00:15:59,766 --> 00:16:01,666
on top of insulating region.

293
00:16:01,666 --> 00:16:05,466
By that way, we can minimize
the overlap area

294
00:16:05,466 --> 00:16:07,666
between semiconductor
and insulator.

295
00:16:07,666 --> 00:16:09,833
But still,
the backside of the channel

296
00:16:09,833 --> 00:16:11,400
is interfacing the material.

297
00:16:11,400 --> 00:16:14,433
So, as long as there's
an insulating material

298
00:16:14,433 --> 00:16:17,600
and semiconductor material
contacting each other,

299
00:16:17,600 --> 00:16:21,766
we are intrinsically not free
from localized charge effect.

300
00:16:21,766 --> 00:16:26,433
So, the next generation is, what
if we, like, fully surround?

301
00:16:26,433 --> 00:16:30,633
I mean, making a silicon channel
suspended into the air

302
00:16:30,633 --> 00:16:33,800
and then fully surrounded
by the gate conductor.

303
00:16:33,800 --> 00:16:39,000
By that way, we can minimize
the impact of isolation.

304
00:16:39,000 --> 00:16:41,866
But still, even though
the volume and thickness

305

00:16:41,866 --> 00:16:43,400
is very thin
in the gate oxide,

306
00:16:43,400 --> 00:16:45,633
but as long as the semiconductor

307
00:16:45,633 --> 00:16:47,933
is interfacing
with the gate oxide,

308
00:16:47,933 --> 00:16:53,266
it's not completely free
from the radiation effect.

309
00:16:53,266 --> 00:16:56,500
So, what I suggested here is,
what if we remove?

310
00:16:56,500 --> 00:16:58,766
Remove the gate oxide,
which is solid,

311
00:16:58,766 --> 00:16:59,966
into the vacuum.

312
00:16:59,966 --> 00:17:03,400
'Cause a vacuum is also
an insulator, right?

313
00:17:03,400 --> 00:17:06,233
So, vacuum can work
as an insulator.

314
00:17:06,233 --> 00:17:09,166
Maybe it's not as efficient
as silicon dioxide,

315
00:17:09,166 --> 00:17:11,200
but it's still an insulator.

316
00:17:11,200 --> 00:17:17,033
So, if the vacuum is surrounding
the silicon nanowire channel,

317
00:17:17,033 --> 00:17:20,933
then there's no material
contacting to the channel.

318
00:17:20,933 --> 00:17:23,666
It's fully suspended,
floating, right?

319
00:17:23,666 --> 00:17:26,466
So, there is no material
that's being damaged,

320
00:17:26,466 --> 00:17:30,000
being, like, degraded
upon the space radiation.

321
00:17:30,000 --> 00:17:33,300
That was my first generation
of idea.

322
00:17:35,366 --> 00:17:39,433
So, uh, this is brief history.

323
00:17:39,433 --> 00:17:40,900
So, in order to prevent--

324
00:17:40,900 --> 00:17:45,333
the figure on the left
is the parasitic transistor path

325
00:17:45,333 --> 00:17:47,600
formed in the bulk region
of the silicon.

326

00:17:47,600 --> 00:17:50,233
Then, in order
to remove that region--

327
00:17:50,233 --> 00:17:53,566
so we used to make a device

328
00:17:53,566 --> 00:17:55,600
on top of some
insulating region.

329
00:17:55,600 --> 00:17:58,100
By that way,
this N-type transistor

330
00:17:58,100 --> 00:18:01,033
and P-type transistor
are electrically decoupled.

331
00:18:01,033 --> 00:18:04,166
So, we don't have to worry
about the--

332
00:18:04,166 --> 00:18:09,833
the parasitic--I mean,
positive feedback loop.

333
00:18:09,833 --> 00:18:13,666
But even in single transistor,
later on, the scientists

334
00:18:13,666 --> 00:18:17,066
discovered that even there
is no, I mean,

335
00:18:17,066 --> 00:18:21,500
N-type and P-type transistor
within only a single transistor,

336
00:18:21,500 --> 00:18:26,300

it still can be upset
upon the radiation

337
00:18:26,300 --> 00:18:30,766
because this body area,
each channel area

338
00:18:30,766 --> 00:18:33,333
is electrically floating, right?

339
00:18:33,333 --> 00:18:36,733
So, when the space radiation
generates

340
00:18:36,733 --> 00:18:40,766
electron-hole pairs
within the silicon channel,

341
00:18:40,766 --> 00:18:45,500
the excess amount
of generated charges,

342
00:18:45,500 --> 00:18:47,000
there's no way to dissipate.

343
00:18:47,000 --> 00:18:51,166
So, it is accumulated
only inside of a channel.

344
00:18:51,166 --> 00:18:55,266
So, these generated charges
work as another source

345
00:18:55,266 --> 00:18:57,000
of the input current.

346
00:18:57,000 --> 00:19:00,666
So, this input current
turns the device on.

347
00:19:00,666 --> 00:19:06,166
So even--not only for the
N-type and P-type transistor,

348
00:19:06,166 --> 00:19:10,033
but only when--even within
the single transistor

349
00:19:10,033 --> 00:19:13,366
that can cause an error.

350
00:19:13,366 --> 00:19:16,700
So, second trial.

351
00:19:16,700 --> 00:19:19,166
So...

352
00:19:19,166 --> 00:19:22,866
if you think how these, uh,

353
00:19:22,866 --> 00:19:28,166
density of generated charges
are formed,

354
00:19:28,166 --> 00:19:32,200
then you can easily imagine
that the charges' density

355
00:19:32,200 --> 00:19:35,833
created by the space radiation
should be proportional

356
00:19:35,833 --> 00:19:38,700
to the volume
of the channel itself.

357
00:19:38,700 --> 00:19:43,500
So, the larger volume means
the larger the ionization.

358
00:19:43,500 --> 00:19:47,666
So, this is the history,
how we evolved the--

359
00:19:47,666 --> 00:19:50,200
how we have evolved
the device structure.

360
00:19:50,200 --> 00:19:53,233
So, basic idea is to minimize
the volume of the--

361
00:19:53,233 --> 00:19:55,600
volume of the channel.

362
00:19:55,600 --> 00:19:59,333
So, we used to build
a thick, thick,

363
00:19:59,333 --> 00:20:02,700
relatively thick channel,
but to minimize the volume

364
00:20:02,700 --> 00:20:04,966
of the radiation sensitive
volume,

365
00:20:04,966 --> 00:20:06,833
then we reduced the thickness.

366
00:20:06,833 --> 00:20:09,800
And then we went
to the silicon nanowire.

367
00:20:09,800 --> 00:20:14,133
But ultimately,
what if we use nothing?

368

00:20:14,133 --> 00:20:16,633
So, if we follow this trend.
So, if we--

369
00:20:16,633 --> 00:20:19,366
so, we know the vector,
how the trend goes up,

370
00:20:19,366 --> 00:20:22,166
then we can, like,
jump into all the way,

371
00:20:22,166 --> 00:20:23,233
down below.

372
00:20:23,233 --> 00:20:25,433
So, it can be zero in volume,
right?

373
00:20:25,433 --> 00:20:27,566
Which means the vacuum.

374
00:20:27,566 --> 00:20:31,333
So, this is my second strategy

375
00:20:31,333 --> 00:20:34,966
to mitigate the error.

376
00:20:34,966 --> 00:20:36,866
So, these are two structures.

377
00:20:36,866 --> 00:20:40,400
First one is, like,
a near-term future.

378
00:20:40,400 --> 00:20:43,366
So, using silicon nanowire
transistor

379

00:20:43,366 --> 00:20:45,466
surrounded by the silicon--
I mean,

380
00:20:45,466 --> 00:20:48,000
surrounded by the vacuum
as a gate dielectric,

381
00:20:48,000 --> 00:20:52,033
the ultimate goal
is to make fully a vacuum

382
00:20:52,033 --> 00:20:54,366
as a charge-carrying material

383
00:20:54,366 --> 00:20:57,766
as it was
a gate insulating material.

384
00:20:59,533 --> 00:21:03,166
So, this is the device I made.
[chuckles]

385
00:21:03,166 --> 00:21:05,200
So, there is a source and drain.

386
00:21:05,200 --> 00:21:09,466
And the gate is fully
surrounding the channel,

387
00:21:09,466 --> 00:21:12,666
but it's not seen
because the gate hides,

388
00:21:12,666 --> 00:21:14,566
covers the channel region.

389
00:21:14,566 --> 00:21:17,233
And then there is also
the vacuum gap

390
00:21:17,233 --> 00:21:20,800
between the source--
I mean, channel and the gate.

391
00:21:20,800 --> 00:21:22,466
So, I made a device.

392
00:21:22,466 --> 00:21:25,433
So, the plot
on the right-hand side

393
00:21:25,433 --> 00:21:30,066
is a very
representative graph of the

394
00:21:30,066 --> 00:21:31,933
current across
the source and drain

395
00:21:31,933 --> 00:21:34,566
controlled by the third
terminal, which is gate.

396
00:21:34,566 --> 00:21:38,033
So, it showed
very good characteristics,

397
00:21:38,033 --> 00:21:43,666
but one counter--counter-offense
I can--being asked

398
00:21:43,666 --> 00:21:49,333
is that--so we want to have
the good control of the gate

399
00:21:49,333 --> 00:21:51,933
toward the channel,

400

00:21:51,933 --> 00:21:54,233
so we want to have
good electrostatic control

401
00:21:54,233 --> 00:21:56,466
from the gate to a channel

402
00:21:56,466 --> 00:21:58,700
so, in order to have a good
electrostatic control,

403
00:21:58,700 --> 00:22:02,066
we want to have
a high dielectric constant

404
00:22:02,066 --> 00:22:04,033
of insulating material.

405
00:22:04,033 --> 00:22:06,100
But as you can imagine,

406
00:22:06,100 --> 00:22:09,966
the vacuum is the--has the
lowest dielectric constant

407
00:22:09,966 --> 00:22:12,400
found in the Earth,
which has a 1.

408
00:22:12,400 --> 00:22:14,233
But, for example,

409
00:22:14,233 --> 00:22:15,900
the silicone dioxide
basically becomes

410
00:22:15,900 --> 00:22:19,933
a very widely used material,
which has around 4

411
00:22:19,933 --> 00:22:22,766
dielectric constant,
but the vacuum is--

412
00:22:22,766 --> 00:22:25,233
has very poor
dielectric properties.

413
00:22:25,233 --> 00:22:29,600
So, uh, there is parameters

414
00:22:29,600 --> 00:22:31,333
called "scaling lengths,"

415
00:22:31,333 --> 00:22:34,500
which signifies how
this device can

416
00:22:34,500 --> 00:22:37,400
control the on and off.

417
00:22:37,400 --> 00:22:40,266
So, if you look at this
characteristic length,

418
00:22:40,266 --> 00:22:43,900
the model, then
the electrostatic control

419
00:22:43,900 --> 00:22:46,933
is not only functional
dielectric constant itself,

420
00:22:46,933 --> 00:22:50,933
but there's some physical term
there, so

421
00:22:50,933 --> 00:22:53,566
what--what this model

tells us is that

422
00:22:53,566 --> 00:22:56,400
if we make a very thinner
and thinner and thinner

423
00:22:56,400 --> 00:22:59,766
thinner thick--
I mean, thinner the gap,

424
00:22:59,766 --> 00:23:03,066
it increase the better and
better electric--

425
00:23:03,066 --> 00:23:05,366
I mean, electrostatic control.

426
00:23:05,366 --> 00:23:10,766
So, it can overcome this
poor dielectric constant.

427
00:23:10,766 --> 00:23:17,300
So, here it comes to
the space radiation test.

428
00:23:17,300 --> 00:23:20,066
Of course, we didn't
shoot it to the space,

429
00:23:20,066 --> 00:23:22,366
but we can emulate
the space radiation

430
00:23:22,366 --> 00:23:24,833
by using some
radiation irradiator

431
00:23:24,833 --> 00:23:25,933
on Earth, so

432
00:23:25,933 --> 00:23:29,400
I tested the gamma ray
and gamma ray

433
00:23:29,400 --> 00:23:32,600
on the gate around
the nanowire transistor

434
00:23:32,600 --> 00:23:34,333
and then, as you can imagine,

435
00:23:34,333 --> 00:23:36,733
as there is noth--
no material that being--

436
00:23:36,733 --> 00:23:38,633
I mean,
damaged by the radiation.

437
00:23:38,633 --> 00:23:41,066
The higher radiation does not

438
00:23:41,066 --> 00:23:43,600
shift any
device characteristics here.

439
00:23:45,266 --> 00:23:47,633
So, let me move into

440
00:23:47,633 --> 00:23:51,266
the vacuum channel transistor.

441
00:23:52,600 --> 00:23:58,100
So, some of you guys seen
the vacuum tube.

442
00:23:58,100 --> 00:24:00,666
So, actually the vacuum tube,
like,

443
00:24:00,666 --> 00:24:05,700
sparked the electronics era
back in 1940s, right?

444
00:24:05,700 --> 00:24:09,766
So, we have seen that some
glowing the vacuum tube

445
00:24:09,766 --> 00:24:14,133
for very high-fidelity
speaker amplifier

446
00:24:14,133 --> 00:24:15,666
in audio system.

447
00:24:15,666 --> 00:24:18,533
So, still, there is some use
for the vacuum tube,

448
00:24:18,533 --> 00:24:21,633
but most of our
modern electronics

449
00:24:21,633 --> 00:24:24,066
are relying on
solid-state device.

450
00:24:24,066 --> 00:24:27,600
But, if you look at the history,
why the vacuum tube

451
00:24:27,600 --> 00:24:29,900
went the dinosaur way,

452
00:24:29,900 --> 00:24:33,766
but that the vacuum--
I mean, solid-state device

453

00:24:33,766 --> 00:24:36,500
become a work horse
for modern electronics is

454
00:24:36,500 --> 00:24:40,333
not because silicon is better
than the vacuum

455
00:24:40,333 --> 00:24:42,800
as a carrier,
charge-carrying material.

456
00:24:42,800 --> 00:24:46,033
But, there's another aspect
that--that

457
00:24:46,033 --> 00:24:50,000
took--for the transistor--
took the vacuum tube's role.

458
00:24:50,000 --> 00:24:53,333
So, intrinsically speaking,

459
00:24:53,333 --> 00:24:57,200
the vacuum is a better
charge-carrying material

460
00:24:57,200 --> 00:24:59,633
than silicon because there's
no--nothing there.

461
00:24:59,633 --> 00:25:03,866
So, in the case of silicon,
the carriers are

462
00:25:03,866 --> 00:25:07,800
scattered or colliding
with the silicon materials.

463
00:25:07,800 --> 00:25:12,666

So, it actually degrade
the drive-current capability.

464
00:25:12,666 --> 00:25:15,700
But in a vacuum,
there's nothing,

465
00:25:15,700 --> 00:25:21,166
so, theoretically speaking,
it can get to the speed of light

466
00:25:21,166 --> 00:25:23,100
for the electron transport.

467
00:25:23,100 --> 00:25:24,633
So, in terms of performance,

468
00:25:24,633 --> 00:25:28,500
the vacuum tube still better
than silicon.

469
00:25:28,500 --> 00:25:33,500
But there was a huge drawback
of the vacuum tube.

470
00:25:33,500 --> 00:25:35,000
So, one of the vacuum--

471
00:25:35,000 --> 00:25:38,633
the drawback
of the vacuum tube is this.

472
00:25:38,633 --> 00:25:43,200
So, even though we are--
we--we use the term "vacuum,"

473
00:25:43,200 --> 00:25:47,100
but there's no vacuum;
there's no ideal vacuum.

474
00:25:47,100 --> 00:25:49,466
We can't make it on Earth.

475
00:25:49,466 --> 00:25:52,700
So, in the vacuum tube envelope,

476
00:25:52,700 --> 00:25:55,933
the one issue was packaging,
but the second issue is that

477
00:25:55,933 --> 00:26:00,733
there's some residual gas
found in the vacuum tube.

478
00:26:00,733 --> 00:26:05,933
So, even though the statistics
that--the probability that

479
00:26:05,933 --> 00:26:09,133
electrons can collide
with the residual gas

480
00:26:09,133 --> 00:26:10,733
is relatively low,

481
00:26:10,733 --> 00:26:14,800
but as soon as
they accidentally--

482
00:26:14,800 --> 00:26:17,066
I mean, hitting
the residual gas

483
00:26:17,066 --> 00:26:20,666
actually, these electrons
can ionize the gas

484
00:26:20,666 --> 00:26:23,666
into the ions and the electrons.

485
00:26:23,666 --> 00:26:28,033
And then, as the vacuum tube
is applied certain voltages,

486
00:26:28,033 --> 00:26:33,233
then this ion,
which is relatively very heavy,

487
00:26:33,233 --> 00:26:36,566
bombard into
one of the electron.

488
00:26:36,566 --> 00:26:40,266
So, it degrade
the material property,

489
00:26:40,266 --> 00:26:43,866
the mechanical-structural
property of the electrons.

490
00:26:43,866 --> 00:26:45,900
So, probably you can
imagine that

491
00:26:45,900 --> 00:26:48,600
you have--you may seen
from the Google image that

492
00:26:48,600 --> 00:26:51,133
some--any--a computer,
the engineers actually

493
00:26:51,133 --> 00:26:53,966
replaced the vacuum tube
from one to another, right?

494
00:26:53,966 --> 00:26:57,533
'Cause the one major issue
for the vacuum tube was this.

495
00:26:57,533 --> 00:27:01,833
The lifetime of the vacuum tube
was relatively poor.

496
00:27:01,833 --> 00:27:03,833
But, that was one drawback.

497
00:27:05,666 --> 00:27:09,000
So, I was thinking this.

498
00:27:09,000 --> 00:27:12,000
So, it's basically impossible

499
00:27:12,000 --> 00:27:16,466
to 100% avoid
the collision between

500
00:27:16,466 --> 00:27:19,600
the electron and residual gases.

501
00:27:19,600 --> 00:27:22,800
This is a periodic table,
showing the number--

502
00:27:22,800 --> 00:27:28,433
shown on the periodic table
is the ionization potential,

503
00:27:28,433 --> 00:27:33,200
which means how high voltage
or potential is required

504
00:27:33,200 --> 00:27:37,800
to ionize this atom
into ions and electrons.

505
00:27:37,800 --> 00:27:39,833
So, if you look at

all these numbers,

506
00:27:39,833 --> 00:27:43,366
the--the lowest number we can
find out is rela--

507
00:27:43,366 --> 00:27:45,433
about 5.

508
00:27:45,433 --> 00:27:48,800
So, it means that
in order to ionize this atom

509
00:27:48,800 --> 00:27:52,233
into the--atom into ions,

510
00:27:52,233 --> 00:27:54,066
will--at least--will require
higher than

511
00:27:54,066 --> 00:27:58,366
the 5 electron volt
as energy.

512
00:27:58,366 --> 00:28:01,666
So, what if we make
a vacuum tube that

513
00:28:01,666 --> 00:28:04,566
operate under 5 volts,

514
00:28:04,566 --> 00:28:07,633
which is, maybe,
some battery-relevant voltages?

515
00:28:07,633 --> 00:28:11,333
Then you can let them collide
with the residual gas,

516

00:28:11,333 --> 00:28:15,000
but this collision is not--
the energy for the collision

517
00:28:15,000 --> 00:28:20,566
is not as high as--
high to create ionization.

518
00:28:20,566 --> 00:28:24,400
So, our first target
is to make a vacuum tube

519
00:28:24,400 --> 00:28:26,800
that operate
at less than 5 volt.

520
00:28:26,800 --> 00:28:29,333
That was first criteria.

521
00:28:31,300 --> 00:28:35,000
And then second one is--
is this.

522
00:28:35,000 --> 00:28:38,100
This figure shows
the air molecule.

523
00:28:38,100 --> 00:28:41,200
And the figure on the left
is just less, for example,

524
00:28:41,200 --> 00:28:43,066
for the sake of simplicity,
let's say

525
00:28:43,066 --> 00:28:45,933
this is atmospheric
pressure on the left.

526
00:28:45,933 --> 00:28:50,500

The air distance is quite close.

527
00:28:50,500 --> 00:28:52,933
But, for example,
the figure on the right

528
00:28:52,933 --> 00:28:57,233
is something like

529
00:28:57,233 --> 00:29:00,366
1 millibar in pressure.

530
00:29:00,366 --> 00:29:03,933
Then the distance between
the air--I mean,

531
00:29:03,933 --> 00:29:08,433
between the two
air molecules are very far.

532
00:29:08,433 --> 00:29:13,166
So, this table is a mean-free
path for different pressure.

533
00:29:13,166 --> 00:29:18,533
So, in our ambient pressure,
usually 1 atm,

534
00:29:18,533 --> 00:29:21,200
the mean-free paths
of the air molecule

535
00:29:21,200 --> 00:29:25,566
in the air we are breathing in
is about 17 nanometer.

536
00:29:25,566 --> 00:29:29,533
So, it means that we
feel abundance of airs here

537
00:29:29,533 --> 00:29:31,566
but we can't--
if we zoom in and zoom in,

538
00:29:31,566 --> 00:29:36,133
and magnify all the way up to
beyond 100 nanometer scale,

539
00:29:36,133 --> 00:29:39,833
then there's a chance that
we never see the airs.

540
00:29:39,833 --> 00:29:45,033
So, we can call it as a--
the quasi-vacuum, right?

541
00:29:45,033 --> 00:29:46,333
So, there's two strategy.

542
00:29:46,333 --> 00:29:48,633
If we make a device
extremely small,

543
00:29:48,633 --> 00:29:51,633
there's a chance to--
for the--

544
00:29:51,633 --> 00:29:53,633
chance for the electrons
collide with the air.

545
00:29:53,633 --> 00:29:55,000
Residual air is decrease.

546
00:29:55,000 --> 00:29:58,266
And even though there's
a collision there,

547
00:29:58,266 --> 00:30:01,366

if we make a device
operating below

548
00:30:01,366 --> 00:30:04,066
the battery op--
voltage such as 5 volt,

549
00:30:04,066 --> 00:30:06,600
we can just let them collide.

550
00:30:08,733 --> 00:30:11,233
Then the other,
there's another

551
00:30:11,233 --> 00:30:15,166
little weakness found in
the conventional vacuum tube.

552
00:30:15,166 --> 00:30:19,000
So, you may see that
the vacuum tube is glowing,

553
00:30:19,000 --> 00:30:21,066
that it looks
really beautiful, right?

554
00:30:21,066 --> 00:30:24,900
But, actually that glowing
is not necessary for

555
00:30:24,900 --> 00:30:27,766
their intrinsic operation,

556
00:30:27,766 --> 00:30:32,833
but it is required for
driving extra current.

557
00:30:32,833 --> 00:30:36,100
For example, the vacuum tube,
you see that--

558
00:30:36,100 --> 00:30:38,800
you can actually see
by using our naked eye,

559
00:30:38,800 --> 00:30:40,700
so it's a human scale.

560
00:30:40,700 --> 00:30:43,000
The scale is about
1 millimeter scale.

561
00:30:43,000 --> 00:30:46,000
For that millimeter scale,
in order to extract

562
00:30:46,000 --> 00:30:49,300
the electron out of some--
out of emitter electrodes

563
00:30:49,300 --> 00:30:52,700
we have to, like,
apply 1,000 volts.

564
00:30:52,700 --> 00:30:55,500
But, this is not readily
available

565
00:30:55,500 --> 00:30:58,200
for any--any applications,
right?

566
00:30:58,200 --> 00:31:01,100
So, in order to lower
the operation voltage

567
00:31:01,100 --> 00:31:04,600
in the conventional vacuum tube,
what happened is

568
00:31:04,600 --> 00:31:08,166
we--heating up of
emitter electrodes.

569
00:31:08,166 --> 00:31:12,166
By that way, the heating can
inject extra electrons.

570
00:31:12,166 --> 00:31:14,466
By that way, we can reduce
the operational voltage.

571
00:31:14,466 --> 00:31:16,400
But still,
the operational voltage

572
00:31:16,400 --> 00:31:19,266
of a conventional vacuum tube
is kind of 100 volt.

573
00:31:19,266 --> 00:31:23,700
So, the energy required
to heat up the cathode,

574
00:31:23,700 --> 00:31:27,066
which is an emitter
of electrodes,

575
00:31:27,066 --> 00:31:28,933
consume more energy than

576
00:31:28,933 --> 00:31:31,433
is intrinsically
required for the operation.

577
00:31:31,433 --> 00:31:33,533
So, it's another drawback.

578
00:31:33,533 --> 00:31:39,133

So, if you understand the
how these electrons can emit

579
00:31:39,133 --> 00:31:41,733
from some solid material
into air,

580
00:31:41,733 --> 00:31:44,800
in our classical understanding,
it's impossible to--

581
00:31:44,800 --> 00:31:48,900
for the electrons escaping
from the confined matter

582
00:31:48,900 --> 00:31:50,100
into the air.

583
00:31:50,100 --> 00:31:55,100
But in modern physics,
we now understand that

584
00:31:55,100 --> 00:31:58,633
these electrons can be--
is kept from--out of the

585
00:31:58,633 --> 00:32:00,466
the confined state,

586
00:32:00,466 --> 00:32:03,466
which is called "tunneling,"
quantum effective tunneling,

587
00:32:03,466 --> 00:32:05,533
quantum tunneling.

588
00:32:05,533 --> 00:32:08,300
So, it means that, the
quantum tunneling, in order to

589
00:32:08,300 --> 00:32:11,966
increase the tunneling
actually is very relevant

590
00:32:11,966 --> 00:32:14,833
to electric field
at the surface of electrons,

591
00:32:14,833 --> 00:32:18,833
so, if we can make a device
which has a--

592
00:32:18,833 --> 00:32:22,000
which electrode has
a extremely high electric field,

593
00:32:22,000 --> 00:32:26,533
then--then without actually
heating the device

594
00:32:26,533 --> 00:32:29,633
it actually emits,

595
00:32:29,633 --> 00:32:32,633
the emitter can
emit electron,

596
00:32:32,633 --> 00:32:34,200
sufficient amount of electrons

597
00:32:34,200 --> 00:32:37,466
to--for the required--
required target.

598
00:32:38,633 --> 00:32:43,000
So, this is
a quantum tunneling model.

599
00:32:43,000 --> 00:32:45,200

That if you look at this model,

600
00:32:45,200 --> 00:32:48,566
there's two factors
that we can engineer.

601
00:32:48,566 --> 00:32:51,600
The first one is electric field
at the cathode.

602
00:32:51,600 --> 00:32:54,900
And second parameters
we can engineer

603
00:32:54,900 --> 00:32:57,166
is work function
of the cathode itself.

604
00:32:57,166 --> 00:33:00,600
So, one is kind of
structural matter

605
00:33:00,600 --> 00:33:02,900
and second one
is material matter.

606
00:33:02,900 --> 00:33:06,400
So, if it emits that
by engineering

607
00:33:06,400 --> 00:33:10,100
the structure of the device
and the material of the device,

608
00:33:10,100 --> 00:33:13,933
we can make
a vacuum tube

609
00:33:13,933 --> 00:33:17,900
free from

a heating element.

610
00:33:18,933 --> 00:33:21,933
And the electric field
can be modeled.

611
00:33:21,933 --> 00:33:25,100
The localized--I mean, the
localized field at the surface

612
00:33:25,100 --> 00:33:29,266
of the emitter can be modeled
this kind of equation.

613
00:33:29,266 --> 00:33:32,633
But it's very, I mean,
intuitive that

614
00:33:32,633 --> 00:33:36,366
the sharper electrode,
the higher the electric field

615
00:33:36,366 --> 00:33:41,000
at the tip of the material.

616
00:33:41,000 --> 00:33:44,166
So, here--and then there is--
the first one is

617
00:33:44,166 --> 00:33:46,933
we want to make a device,
I mean,

618
00:33:46,933 --> 00:33:49,200
the emitter tip
as sharp as possible

619
00:33:49,200 --> 00:33:51,400
to intensify the localized
electric field

620
00:33:51,400 --> 00:33:53,566
at the surface--at the tip.

621
00:33:53,566 --> 00:33:57,500
The second one is, uh,
in order to

622
00:33:57,500 --> 00:34:01,033
increase the gate-controlling
efficiency.

623
00:34:01,033 --> 00:34:04,466
So, this is a simulation result
of the electric field

624
00:34:04,466 --> 00:34:08,466
for different gating structure.

625
00:34:08,466 --> 00:34:10,566
The first one is just
planar gating.

626
00:34:10,566 --> 00:34:14,366
The gate is placed
on just top of the emitter tip.

627
00:34:14,366 --> 00:34:17,966
Then if we place the gate
top and bottom,

628
00:34:17,966 --> 00:34:22,433
then it double--
not double, but efficiently

629
00:34:22,433 --> 00:34:24,600
increase the localized field.

630
00:34:24,600 --> 00:34:26,766

And then triple,
increase again,

631
00:34:26,766 --> 00:34:29,000
and then quadruple,
increase further again.

632
00:34:29,000 --> 00:34:32,966
But you can imagine that
the ultimate gating structures,

633
00:34:32,966 --> 00:34:36,633
we can implement
in a three-dimensional world

634
00:34:36,633 --> 00:34:39,133
is actually surrounding
the tip, right?

635
00:34:39,133 --> 00:34:44,300
Then there's no further way
to increase the gating,

636
00:34:44,300 --> 00:34:45,633
other than surround the gate.

637
00:34:45,633 --> 00:34:49,300
So, I was thinking that

638
00:34:49,300 --> 00:34:51,366
we have to make
a very sharp tip,

639
00:34:51,366 --> 00:34:55,366
and we want only to make
a gate which is

640
00:34:55,366 --> 00:34:59,733
fully surrounding
the surface of the gate.

641
00:35:01,133 --> 00:35:05,933
Then this is relatively,

642
00:35:05,933 --> 00:35:07,366
I mean, too technical,

643
00:35:07,366 --> 00:35:11,533
but the message I want to
deliver in this slide is this.

644
00:35:11,533 --> 00:35:15,066
Instead of bulky
three-dimensional materials,

645
00:35:15,066 --> 00:35:18,566
but if we make
a emitter electrode,

646
00:35:18,566 --> 00:35:21,100
which is kind of
one-dimensional fashion,

647
00:35:21,100 --> 00:35:24,633
the one-dimension is kind of
like a whisker type of thing.

648
00:35:24,633 --> 00:35:28,400
Then the transmission
probability becomes better than

649
00:35:28,400 --> 00:35:31,666
its intrinsic material
properties, so--

650
00:35:31,666 --> 00:35:35,600
so it means we can
further engineer

651

00:35:35,600 --> 00:35:37,966
the tunneling probability

652
00:35:37,966 --> 00:35:41,866
by having the nanowire type
of electrode.

653
00:35:41,866 --> 00:35:47,633
So, here it comes to the
fabricated device structure.

654
00:35:47,633 --> 00:35:50,800
So, this is quite similar
to the device

655
00:35:50,800 --> 00:35:53,533
I showed previous slide,

656
00:35:53,533 --> 00:35:57,866
but one difference is that
actually there is an empty gap,

657
00:35:57,866 --> 00:36:02,166
empty cavity within the--
there's the gate,

658
00:36:02,166 --> 00:36:04,533
there's a small hole,
but there's nothing there.

659
00:36:04,533 --> 00:36:08,433
It's hard to see because
it's fully veiled by the gate.

660
00:36:08,433 --> 00:36:11,800
And then there's an emitter,
which is really sharp,

661
00:36:11,800 --> 00:36:15,600
and there's a collector, which

collects the emitted electrons,

662
00:36:15,600 --> 00:36:17,333
but on the other side.

663
00:36:17,333 --> 00:36:21,900
And, again, it showed
a fairly good ID--I mean,

664
00:36:21,900 --> 00:36:26,266
the electrode
current controllability.

665
00:36:28,400 --> 00:36:32,333
And the question I've been
often asked by others is,

666
00:36:32,333 --> 00:36:34,333
how do we create,

667
00:36:34,333 --> 00:36:39,333
like, the cavity
inside of the gate?

668
00:36:39,333 --> 00:36:41,400
This is a fabrication flow.

669
00:36:41,400 --> 00:36:44,733
So, in order to--
as I explained previously,

670
00:36:44,733 --> 00:36:49,100
our target is to create
the empty gap

671
00:36:49,100 --> 00:36:52,366
less than--I mean, free pass
of the air molecule

672

00:36:52,366 --> 00:36:56,366
in our atmospheric pressure,
which was around 17 nanometers,

673
00:36:56,366 --> 00:36:59,766
so, I was targeting to
make a device less than--

674
00:36:59,766 --> 00:37:02,933
a vacuum gap
less than 15 nanometer.

675
00:37:02,933 --> 00:37:07,266
But for the sake of
understanding,

676
00:37:07,266 --> 00:37:11,766
in some--some lab scale,
actually,

677
00:37:11,766 --> 00:37:14,366
the critical dimension
we can create

678
00:37:14,366 --> 00:37:17,733
at the Gibbon
fabrication facility is--

679
00:37:17,733 --> 00:37:19,533
is called a critical dimension.

680
00:37:19,533 --> 00:37:23,766
But the critical dimension
in just regular fab--

681
00:37:23,766 --> 00:37:25,400
in Stanford and UC Berkely,

682
00:37:25,400 --> 00:37:29,100
they offer around,

like, 300 nanometer

683
00:37:29,100 --> 00:37:30,800
as a minimum feature size.

684
00:37:30,800 --> 00:37:34,666
But for Intel, as of now,
Intel can fabricate the device

685
00:37:34,666 --> 00:37:38,466
less than, 17, 14 nanometer
in the--in the scale.

686
00:37:38,466 --> 00:37:40,633
So, there's a huge gap
between industry

687
00:37:40,633 --> 00:37:42,700
and academia
and research institutes,

688
00:37:42,700 --> 00:37:47,200
but my target was beyond,
beyond the critical dimension

689
00:37:47,200 --> 00:37:51,900
that you can, like, to buy,
you can rent their equipment.

690
00:37:51,900 --> 00:37:57,333
So--so, this is
fabrication flow, how we can

691
00:37:57,333 --> 00:38:02,033
get the empty cavity
less than 15 nanometer is this.

692
00:38:02,033 --> 00:38:06,400
So, first we make
a silicon suspending--

693
00:38:06,400 --> 00:38:09,033
suspended silicon,
shown in the Figure A.

694
00:38:09,033 --> 00:38:14,100
The Figure B is we expose
entire silicon nanowire,

695
00:38:14,100 --> 00:38:18,900
the suspended silicon nanowire
into some oxidation process.

696
00:38:18,900 --> 00:38:22,700
Which converts the silicon
into silicon dioxide.

697
00:38:22,700 --> 00:38:26,000
Then I--I expose it
until the central portion

698
00:38:26,000 --> 00:38:29,633
of the silicon nanowire
becomes fully oxidized.

699
00:38:29,633 --> 00:38:33,566
Then this fully-oxidized
nanowire--silicon dioxide,

700
00:38:33,566 --> 00:38:36,300
you're gonna use it as
your sacrificial layer

701
00:38:36,300 --> 00:38:40,600
that gonna be, I mean, removed,
selectively moved later on.

702
00:38:40,600 --> 00:38:44,166
So, traditionally,
the critical feature side

703
00:38:44,166 --> 00:38:46,966
is determined by
the photolithography

704
00:38:46,966 --> 00:38:48,733
but this one,
the critical dimension

705
00:38:48,733 --> 00:38:50,733
has nothing to do
with the photolithography,

706
00:38:50,733 --> 00:38:54,866
but it's controlled
by the oxidation process.

707
00:38:54,866 --> 00:38:57,666
So, in the Figure C,
we deposit the gate material,

708
00:38:57,666 --> 00:38:59,900
and then put on the gate.

709
00:38:59,900 --> 00:39:04,966
Then the site of
sacrificial oxide is exposed.

710
00:39:04,966 --> 00:39:08,166
Then you can just, uh,
well, etch out--

711
00:39:08,166 --> 00:39:12,133
etch out the silicone dioxide,
selectively.

712
00:39:12,133 --> 00:39:14,400
Then we can
make a vacuum gap,

713
00:39:14,400 --> 00:39:17,433
only within the location there.

714
00:39:19,900 --> 00:39:25,633
So--oh, this is probably
final, last slide.

715
00:39:25,633 --> 00:39:29,133
So, also we tested for
the space qualify--

716
00:39:29,133 --> 00:39:30,766
I mean, qualification,

717
00:39:30,766 --> 00:39:33,533
so, we tested under
proton and gamma ray.

718
00:39:33,533 --> 00:39:35,500
And, as we expected,
there's no materials

719
00:39:35,500 --> 00:39:39,800
that being disturbed by
any kind of space radiation.

720
00:39:39,800 --> 00:39:43,300
There's no the device
parameters changes found.

721
00:39:44,766 --> 00:39:47,166
So, here's the end,
so let me specify--

722
00:39:47,166 --> 00:39:51,333
let me wrap up this seminar
by saying:

723
00:39:51,333 --> 00:39:54,133

This technology shows
great promise for making

724
00:39:54,133 --> 00:39:59,533
radiation tolerance integral to
existing electronic architecture

725
00:39:59,533 --> 00:40:03,733
and enabling future deep space
science mission.

726
00:40:03,733 --> 00:40:04,733
Thank you.

727
00:40:04,733 --> 00:40:07,733
[applause]

728
00:40:11,433 --> 00:40:13,700
- So, we have time
for some questions.

729
00:40:13,700 --> 00:40:16,033
If you have a question,
please raise your hand,

730
00:40:16,033 --> 00:40:19,533
wait for the microphone,
and ask one question.

731
00:40:21,166 --> 00:40:22,233
Go ahead.

732
00:40:22,233 --> 00:40:25,000
- Hi, um, so I have
a question about

733
00:40:25,000 --> 00:40:28,233
the practical matter of--
I suppose on Earth,

734
00:40:28,233 --> 00:40:32,000
it's, you know, maybe it's
a bit disadvantage

735
00:40:32,000 --> 00:40:34,266
or a challenge to
have to maintain the vacuum

736
00:40:34,266 --> 00:40:35,566
in your device.

737
00:40:35,566 --> 00:40:37,266
But, on the other hand,
in space,

738
00:40:37,266 --> 00:40:39,800
is it sufficient
to just expose your devices

739
00:40:39,800 --> 00:40:41,933
to space vacuum,
is that a good enough vacuum?

740
00:40:41,933 --> 00:40:43,533
- So, my answer is this.

741
00:40:43,533 --> 00:40:45,500
We have our iPhone, right?

742
00:40:45,500 --> 00:40:48,066
In our iPho--probably you may
have heard about

743
00:40:48,066 --> 00:40:50,133
the technology called MEMS,

744
00:40:50,133 --> 00:40:53,033
the Mechanical-Electro--
Electro-Mechanical Systems,

745
00:40:53,033 --> 00:40:55,466
the Micro-Electronic-Mechanical
Systems.

746
00:40:55,466 --> 00:40:57,766
In our cell phone,
in our iPhone,

747
00:40:57,766 --> 00:41:01,766
we have some gyroscope,
accelerometer, things like that,

748
00:41:01,766 --> 00:41:04,366
which is implemented
by the MEMS.

749
00:41:04,366 --> 00:41:07,333
But, for the MEMS technology,
they are relying on

750
00:41:07,333 --> 00:41:11,033
some freely moving part
within the chip itself.

751
00:41:11,033 --> 00:41:14,666
So, actually,
I'll speak it like that.

752
00:41:14,666 --> 00:41:17,466
The vacuum packaging technology
is already available.

753
00:41:17,466 --> 00:41:19,966
So it's already mature
technology in the market.

754
00:41:19,966 --> 00:41:23,066
So, whether or not we're
gonna use it in the Earth

755
00:41:23,066 --> 00:41:25,866
or the space,
the vacuum packaging,

756
00:41:25,866 --> 00:41:29,100
at the moment we're
gonna implement in reality.

757
00:41:29,100 --> 00:41:32,466
We're gonna package this device
into the real chip then

758
00:41:32,466 --> 00:41:36,666
we have vacuum-packaging
technology ready there.

759
00:41:38,500 --> 00:41:40,166
- Jin-Woo, I have
a question back here.

760
00:41:40,166 --> 00:41:43,966
So, there's technology that's
gone into deep space,

761
00:41:43,966 --> 00:41:46,666
like the "Voyager," for example
that was launched

762
00:41:46,666 --> 00:41:50,500
in the early 1970s,
continues to send

763
00:41:50,500 --> 00:41:52,400
information back to us.

764
00:41:52,400 --> 00:41:55,700
I mean, we have data
from instrumentation

765
00:41:55,700 --> 00:41:57,800
that's been in space
a long time,

766
00:41:57,800 --> 00:42:00,866
that's been exposed--
that's old technology.

767
00:42:00,866 --> 00:42:03,666
Ancient technology
by current standards, right?

768
00:42:03,666 --> 00:42:06,900
How have those
technologies failed,

769
00:42:06,900 --> 00:42:09,400
or was it just redundancy
that allowed them

770
00:42:09,400 --> 00:42:10,533
to survive so long?

771
00:42:10,533 --> 00:42:14,166
I mean, why have we been
so successful?

772
00:42:14,166 --> 00:42:16,366
- So, there is a silly way
to overcome

773
00:42:16,366 --> 00:42:18,166
the space radiation effect.

774
00:42:18,166 --> 00:42:20,866
The most easy one,
most straightforward one

775
00:42:20,866 --> 00:42:24,133

which is actually implemented
one in NASA is

776
00:42:24,133 --> 00:42:28,033
actually shielding the
entire electronic system

777
00:42:28,033 --> 00:42:30,300
by using thick metal.

778
00:42:30,300 --> 00:42:32,766
Which I explained
is actually redundancy

779
00:42:32,766 --> 00:42:36,133
and it cause a payload
and it's a weight penalty.

780
00:42:36,133 --> 00:42:38,500
That's the second--
the first one.

781
00:42:38,500 --> 00:42:41,533
The second approach is

782
00:42:41,533 --> 00:42:44,633
when we design a circuit,

783
00:42:44,633 --> 00:42:47,400
we--there is a
expected performance

784
00:42:47,400 --> 00:42:49,933
we can bring out of the--
through this design.

785
00:42:49,933 --> 00:42:52,733
But, for the space mission,
actually we

786
00:42:52,733 --> 00:42:57,766
use less performance
than it actually give us.

787
00:42:57,766 --> 00:43:02,566
By that way, we can, like,
have a larger tolerance

788
00:43:02,566 --> 00:43:04,133
against the radiation.

789
00:43:04,133 --> 00:43:07,966
So, we are giving up performance
that we can actually attain

790
00:43:07,966 --> 00:43:09,566
from the design.

791
00:43:09,566 --> 00:43:13,066
The third one is
we usually--

792
00:43:13,066 --> 00:43:15,066
I don't know,
not every mission,

793
00:43:15,066 --> 00:43:17,933
but some missions, for the
mission critical components,

794
00:43:17,933 --> 00:43:23,966
we put, like, two or three
exactly the same chips

795
00:43:23,966 --> 00:43:27,500
and then they're gonna use
them one by one.

796
00:43:27,500 --> 00:43:30,000

So, by that way,
we can extend the lifetime,

797
00:43:30,000 --> 00:43:33,800
but again, this is also
expensive and redundant.

798
00:43:33,800 --> 00:43:36,800
But my technology is
intrinsically free from

799
00:43:36,800 --> 00:43:40,133
the space radiation damage.

800
00:43:41,900 --> 00:43:44,900
- A following question,
in biological systems,

801
00:43:44,900 --> 00:43:46,833
the solution is to do repair.

802
00:43:46,833 --> 00:43:49,133
Have you considered

803
00:43:49,133 --> 00:43:52,233
systems that would be
somehow self-repairing?

804
00:43:52,233 --> 00:43:54,100
- It's really good question.

805
00:43:54,100 --> 00:43:57,100
And that actually we
submit some proposal

806
00:43:57,100 --> 00:44:01,000
to mimic the human immune system
in electronics, so

807

00:44:01,000 --> 00:44:05,866
what is a--the self-immune
electronic system?

808
00:44:05,866 --> 00:44:09,666
We propose some proposal,
so we are awaiting that.

809
00:44:09,666 --> 00:44:12,266
So, yeah, we have.

810
00:44:19,766 --> 00:44:21,233
- So, thank you very much.

811
00:44:21,233 --> 00:44:23,566
Please join me
in thanking Dr. Han again

812
00:44:23,566 --> 00:44:24,700
for an excellent talk.

813
00:44:24,700 --> 00:44:25,700
Thank you.

814
00:44:25,700 --> 00:44:28,700
[applause]