Fowler--Nordheim Tunneling at Sharp-Shaped Floating Gate Structure Modeled as Triangular Electrode

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***Abstract*—The poly to poly tunneling mechanism in a split gate memory device was studied using the Fowler-Nordheim equation. The electric field distribution between a sharp-shaped floating gate and its split gate pair was calculated by modeling the sharp floating gate as a triangular electrode. The electric field expression was then used to calculate the tunnel current density, evaluated both at low and high bias, which resemble the erasing process in a flash memory device. The results were compared with those published by Silicon Storage Technology (SST) as the inventor. It was shown that the two-tunnel current density profiles are different at a low bias regime but become more similar as the applied bias increases. This dissimilarity results from the difference in geometry used to model the sharp-tip floating gate. In spite of the discrepancy at low regime bias, it is argued that this triangular electrode model is still adequate for use as a qualitative model to simulate the erasing process, which is known to be done at high applied voltage.**

***Index Terms*—Fowler--Nordheim, sharp electrode, tunnel current density**

I. INTRODUCTION

The split-gate flash memory from SST is a memory device that is well konwn for its low power consumption. Basically, two major innovations are applied in this structure. Firstly, enhanced programming efficiency by using a mechanism called Source-Side Injection (SSI), which is said to have a higher hot carrier injection rate compared to the usual Channel Hot Electron Injection (CHEI) [1]. The SSI mechanism is made possible by splitting the top polysilicon gate into two parts, namely a control gate (located on top of the floating gate), and a split gate (located side by side with the floating gate). Meanwhile, the efficiency of erasing is also claimed to be increased by employing a modified floating gate structure with a sharp-tip at both ends. This sharp profile is said to enhance the tunneling rate. The split gate flash memory cell is illustrated in Fig. 1 as in [2].

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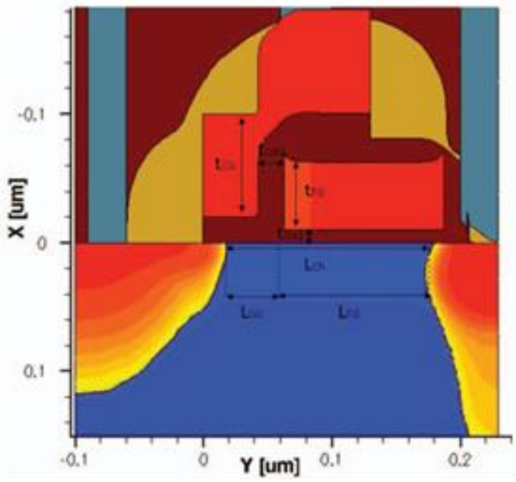

Figure 1. Split gate flash memory with sharp floating gate

II. METHOD

First we analytically derived the expression of the electric potential distribution between the sharp floating gate with the split gate above it. In doing so, three assumptions were made to simplify the case being studied [3]:

- The n+ polysilicon electrodes were assumed to behave like metal.
- There was assumed to be no trapped or free charge inside the oxide layer between the floating gate and the split gate.
- The electrical bias at the electrode was assumed to be given exactly.

The sharp shaped floating gate was modelled as a triangular metal electrode as illustrated in Fig. 2.

The electric potential distribution surrounding the sharp tip can be obtained by solving the Laplace equation, evaluated in polar coordinates [4]:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\varphi}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2\varphi}{\partial\phi^2} \quad (1)$$

Solving (1) for φ, the electric field distribution can then be expressed as follows:

$$\vec{F}_{(z)}=-\frac{\partial\varphi}{\partial z} \quad (2)$$

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Having derived the electric potential distribution, the expression is used to calculate the tunnel current density. The Fowler--Nordheim tunneling equation was used, which reads [5]:

$$J_{FN} = (a\, F^2)\exp(-b\, F^{-1}) \tag{3}$$

where a and b are the first and second Fowler--Nordheim constant, respectively:

$$a = \frac{q^3}{8\pi h}\frac{m_0}{m_{eff}}\frac{1}{\Phi} \tag{4}$$

$$b = \frac{4}{3}\frac{\sqrt{2m_{eff}\Phi^3}}{hq} \tag{5}$$

For reference, the tunnel current density from SST was used, which employs a cylindrical geometry to model the floating gate structure [6]. The electric field expression is as follows:

$$F = \frac{V_{Ox}-[0.34\Phi\ln(1+T_{Ox}/r)]}{r\,\ln(1+T_{Ox}/r)} \tag{6}$$

and its tunnel current density is governed by a Fowler--Nordheim--like equation:

$$J = a\left(\frac{3.2}{\Phi}\right)F^2\exp\left[\frac{-b}{F}\left(\frac{\Phi}{3.2}\right)^{3/2}\right] \tag{7}$$

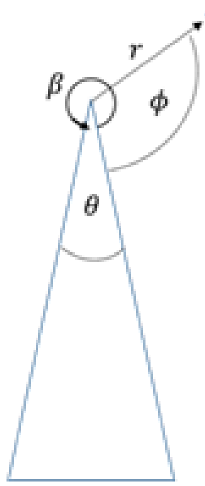

Figure 2. Sharp floating gate modeled as triangular electrode

III. Results and Discussions

A. Tunnel Current Density Profiles

By evaluating (1) and (2), we get the expressions for the electric potential and the electric field respectively as:

$$\varphi_{(r,\phi)} = V\left(\frac{z}{d}\right)^{\frac{m\pi}{\beta}}\sin\left(\frac{m\pi}{\beta}\phi\right) \tag{8}$$

$$\vec{F}_{(z)} = -V\left(\frac{1}{d}\right)^{\frac{\pi}{\beta}}\sin\left(\frac{\pi}{\beta}\phi\right)\frac{\pi}{\beta}(z)^{\frac{\pi}{\beta}-1} \tag{9}$$

Using (3) and (7) we get the tunnel current density profiles shown in Fig. 3. It can be seen that both curve are differ significantly in the low bias range. This can be attributed to several factors. Firstly, it turns out that the triangular model we used to derive the electric field expression has a limiting factor, namely that this model is inadequate to exactly express the electric field at the electrode surface. This is a result of the geometry used to describe the model electrode. The simple triangular model used here requires the zero point coordinate (r in polar coordinates) to start at the electrode's surface. Consequently, inserting z equal to zero would lead to the electric field becoming infinite. So instead it was tried to evaluate F at an arbitrary point near the edge. We defined near to one hundredth of total electrode separation. In this case, the curves above resulted from evaluation of F at 0.2 nm above the tips edge.

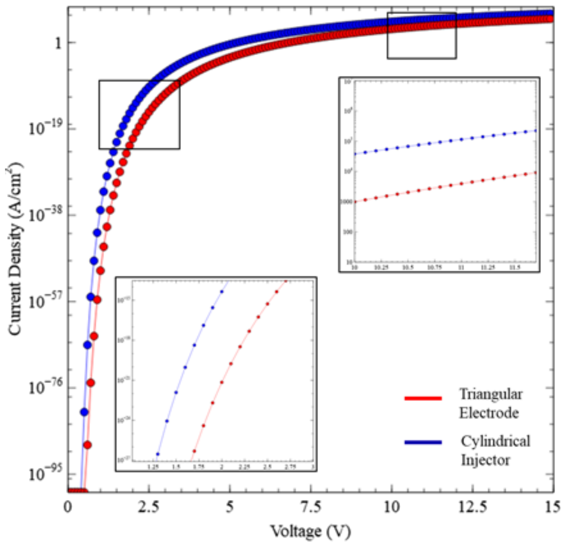

Figure 3. Tunnel current comparison from two different electrode models

In short, the Fowler--Nordheim tunnel profile of the triangular electrode model was taken at a slightly different point compared to the one from the cylindrical injector model (which is evaluated using the electric field value at the injector surface) and hence, may result in a different tunnel current profile. Secondly, the most important factor that gives rise to the dissimilarity between the two profiles comes from the fact that we used a different geometrical model than SST. The triangular model used here is a 2D model with its 3D counterpart being a wedge shape, while SST used a cylindrical injector model. A comparison between the two geometries are shown in Fig. 4.

It is known that electrical charge distributions are highly dictated by the geometrical shape of the object they are confined within [7]. We presumed that the cylindrical injector model used by SST is a 3D injector as depicted in Fig. 4A. This is because Fowler--Nordheim tunneling occurs at a lower bias in the cylindrical injector model, which indicates a higher electric field. The relation between the electric field at the cylindrical/triangular electrode's surface and the applied voltage at a reference electrode 20 nm away can be seen in Fig. 5. Note that, although electric field F from the injector model increase much more rapidly in the high bias region compared to the triangular model, when it comes to FN tunnel current calculation, the exponential part of (7) will balance this behavior, leading to a reduced difference between the FN tunnel curve of both models, as depicted in Fig. 3.

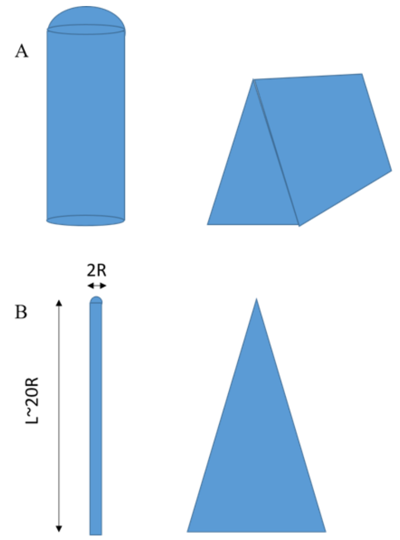

Figure 4. Illustration of geometrical difference between the two models used in this study in (A) 3D and (B) 2D

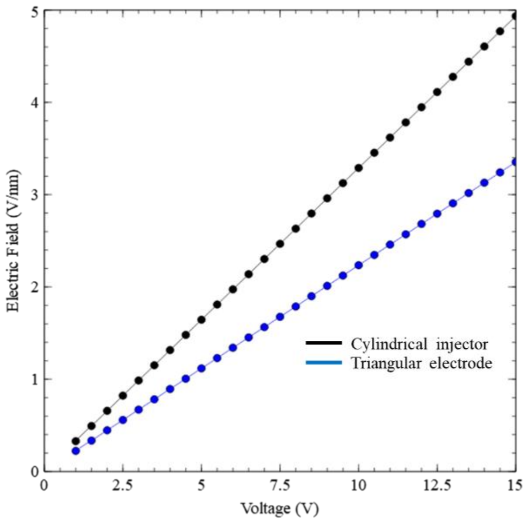

Figure 5. Electric field at electrode's surface under several applied bias

B. *Effect of θ and d*

Knowing the general current density profile of the triangular electrode, we tried to look at how the geometrical parameters of our model affect the resulting tunnel current density. Fowler--Nordheim tunnel profiles for different opening angle values are shown in Fig. 6.

Generally, it can be seen that the tunnel current is inversely proportional to the opening angle as indicated by (9). Mathematically, for a sharp electrode (i.e.$0 < \theta < \pi$), the $(\pi/\beta - 1)$ will have a value between -0.5 and 0, while a lower θ will also lower the $(\pi/\beta - 1)$ value towards -0.5, corresponding to the higher electric field F. Physically, a lower opening angle means a higher surface charge density, which leads to an increased electric field.

Meanwhile, we found that variation in electrode separation d has an effect that is more noticable compared to variation of the opening angle as shown by Fig. 7. The reason for this is that opening angle θ is more constrained than d, θ can only varied between 0 and some value under π (it can not even reach π, since opening angle of π means that our electrode is no longer "sharp-shaped") so it can be understood that variation in θ are only gives slight differences in tunnel current profile. Meanwhile, d is practically more free to be defined and hence, has a more significant effect on the final Fowler--Nordheim profile.

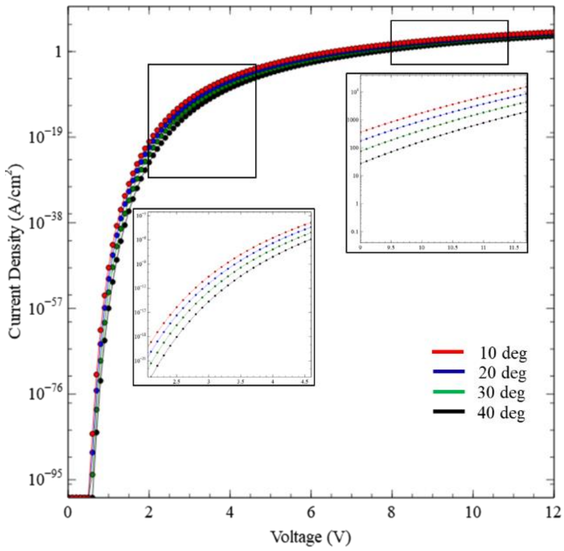

Figure 6. Comparison of tunnel current density of triangular electrode with different opening angle θ

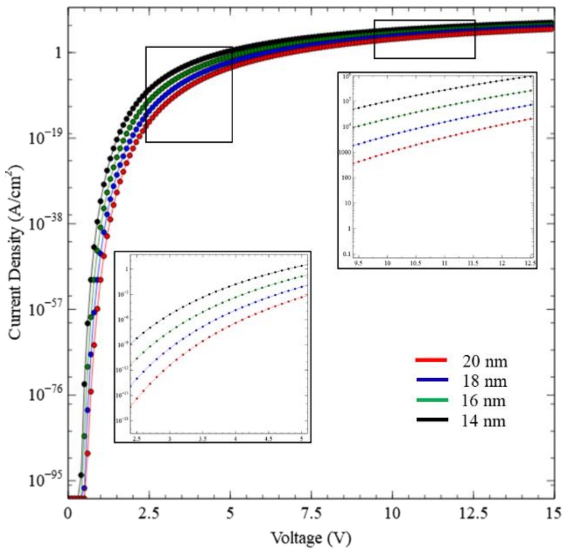

Figure 7. Comparison of tunnel current density of triangular electrode with different inter-electrode separation *d*

IV. Conclusion

A study of quantum tunneling phenomena occuring in an SST split gate flash memory device during erasing was conducted. The tunnel current density profile obtained from the Fowler--Nordheim formulation was applied to two different electrode models for comparison. The dimensional triangular electrode models were used and compared to the cylindrical injector model used by Kotov *et al.* from SST. It was shown that the resulting tunnel current density profiles differ in the low regime bias but continue to resemble each other once the applied bias is increased. This difference comes from the difference in electric field enhancement at the electrode surface. This difference affects the final Fowler--Nordheim current, which is known for its dependence on the electric field value at the tunneling surface. Meanwhile, the effect of opening angle and electrode separation on the tunnel current density was also examined. It turned out that electrode separation affects tunnel current more significantly, relative to the opening angle variation.

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