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High Emission Dispenser Cathodes with Innovative Impregnant

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2020.05.26

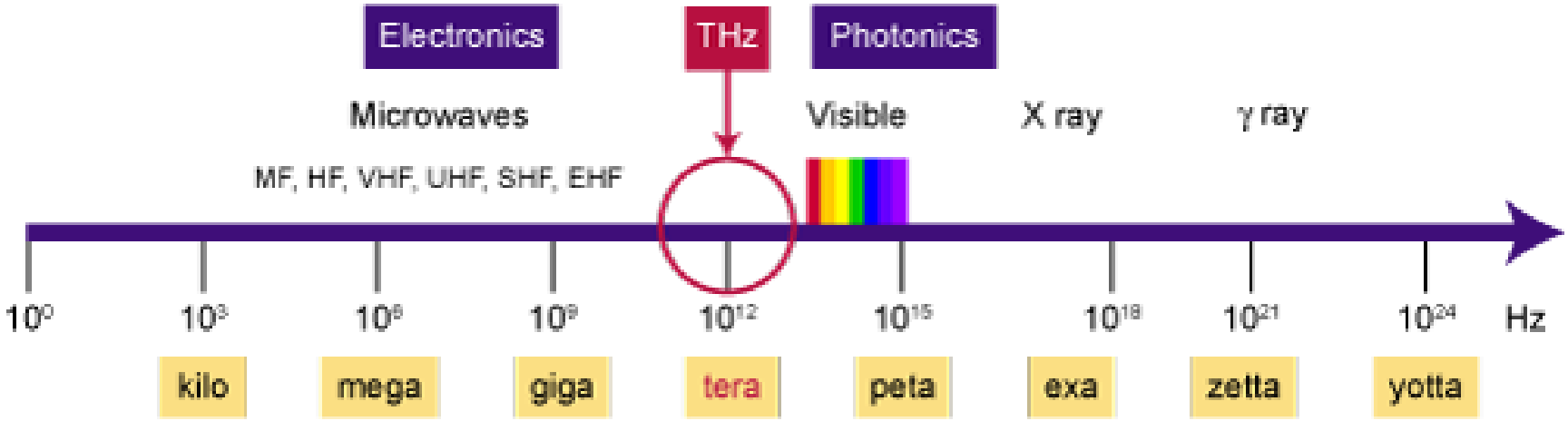
Outline

1. Introduction
2. Experiments
3. Results
4. New Model for Scandate Cathode
5. Summary

Introduction

Demand and Challenge

Terahertz wave devices put forward an ascending demand for high emission cathode



Current Density: 20, 40, 60, 80, 100 A/cm²

Introduction

Two milestones of scandate cathodes show great potential, **but** problems still exist…

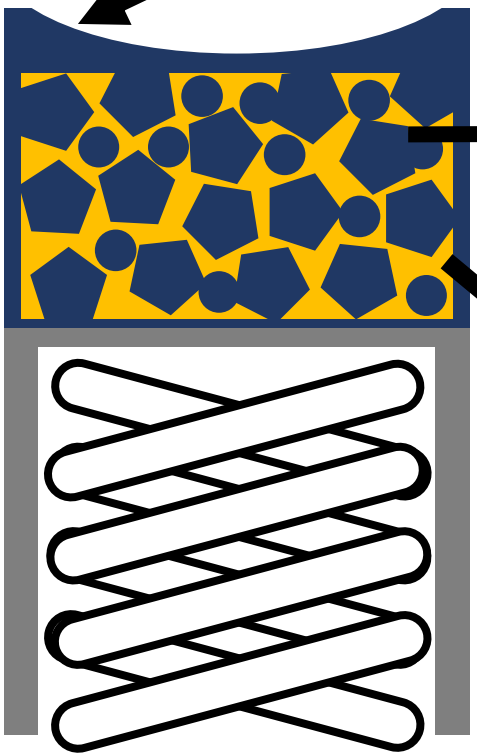
Laser Ablation Deposition- Top Layer
Laser power is changing;
Active target is sensitive to the environment.

1997
G. Gaertner,
P. Geittner,
H. Lydtin, et al.

Body doping scandate- Matrix
Not easy for high-tempreture brazing in H_2;
Not suitable for precisely machining and centring.

2003
Jinshu Wang,
Yiman Wang,
Siwu Tao, et al.

Introduction



Film or layer
Top Layer Deposition

Tungsten sponge
Doped Matrix

Active Substance
old, but wild

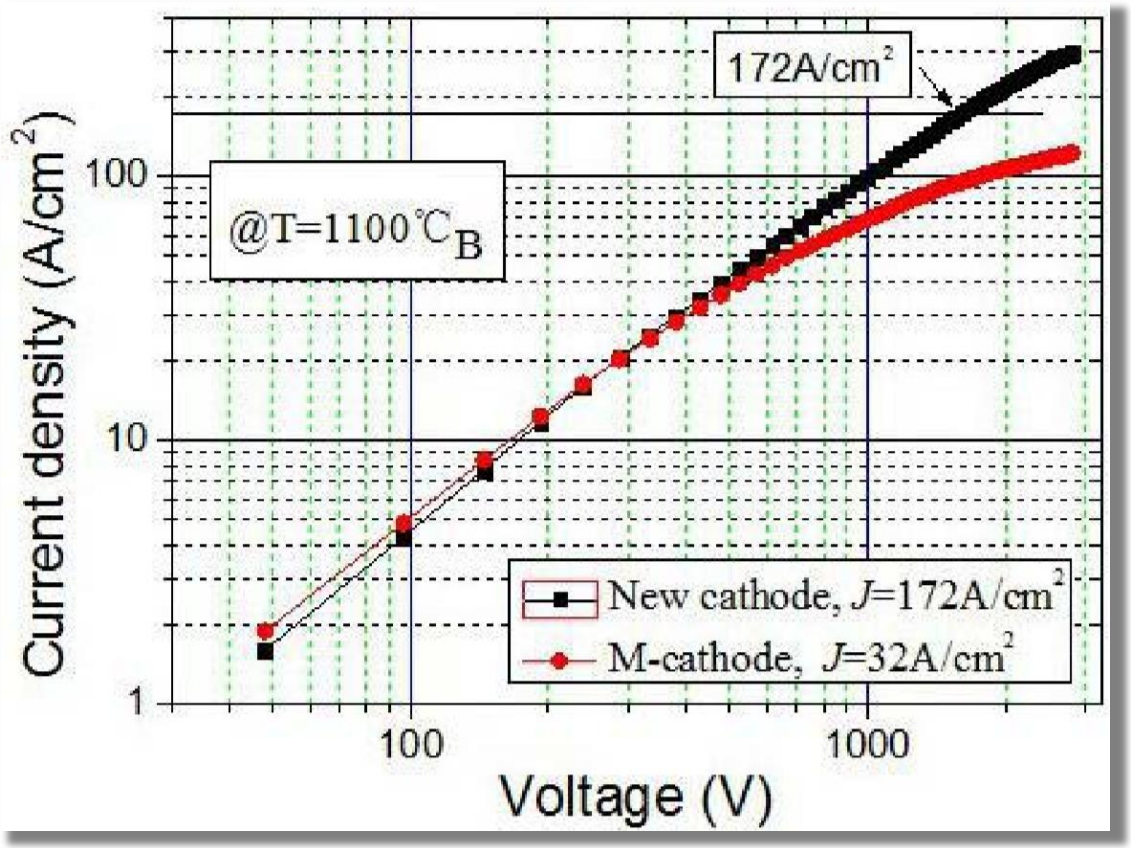
Previous Researches

New Idea

Develop Innovative Active Substance

Introduction

Innovative Active Substance



2013

$26BaO \cdot 29SrO \cdot 8Sc_2O_3 \cdot 7CaO \cdot Al_2O_3$

Current Density: 172A/cm² at 1100℃B

(Water-cooled anode planar diode test, Pulse Set: 20Hz 5μs)

Shengyi Yin, Zhaochuan Zhang, et al.,
IEEE Transaction on Electron Devices, (2013) 4258.

Introduction

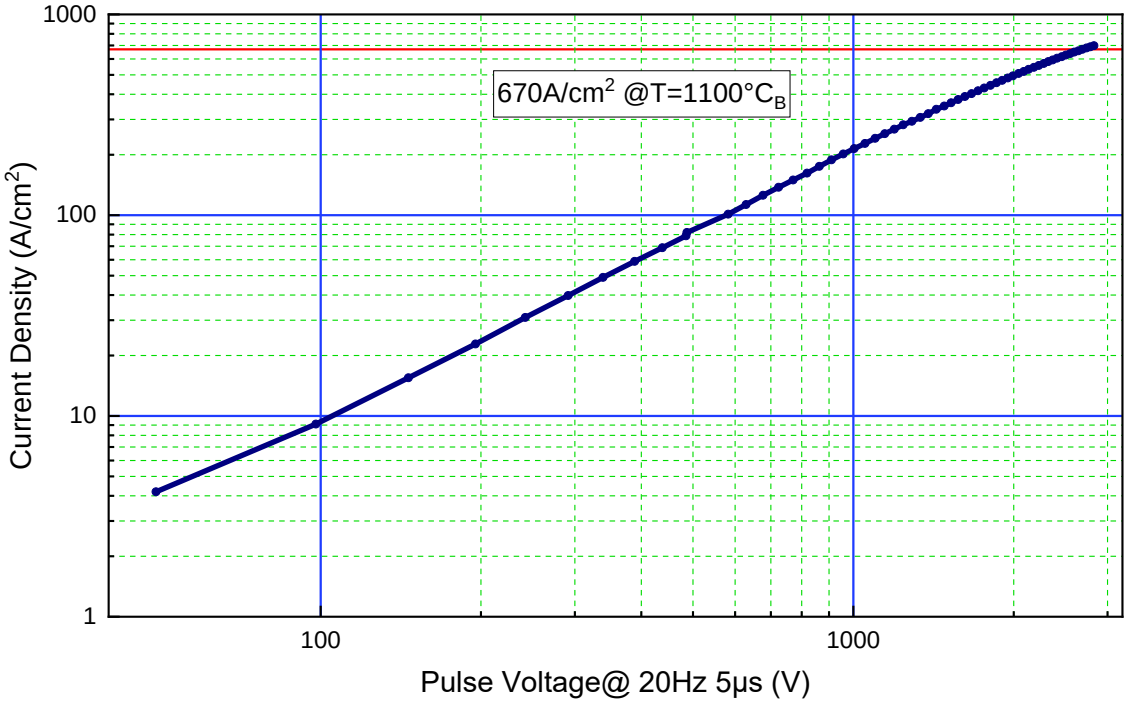
Freeze Sublimation Method

2019

Novel material of Ba_2ScAlO_5 + 3%at SrO was discovered.

Freeze-drying method was first used for the preparation of impregnant.

Typical Current Density: **670A/cm²** at 1100℃$_B$
↑2.8 times



Experiments

- **Precursor Preparation**

- **Analyses & Characterizations of the New Substance**
  - **XRD:** Phase Composition & Structure
  - **Melting Point Test:** Impregnation Temperature
  - **SEM-EDS:** Particle Size & Elementary Distribution Uniformity

- **Preparation of Cathodes and Electron Guns**
  - **Cathode Preparation:**
    Brazing → Heater Assembly → Impregnation → Machining

- **Emission test**

- **Application**

Experiments

Precursor Preparation

Acetates or Nitrates of Ba, Sr, Al and Sc

Solution Mixing & Stirring

Liquid N_2 Instant Freeze

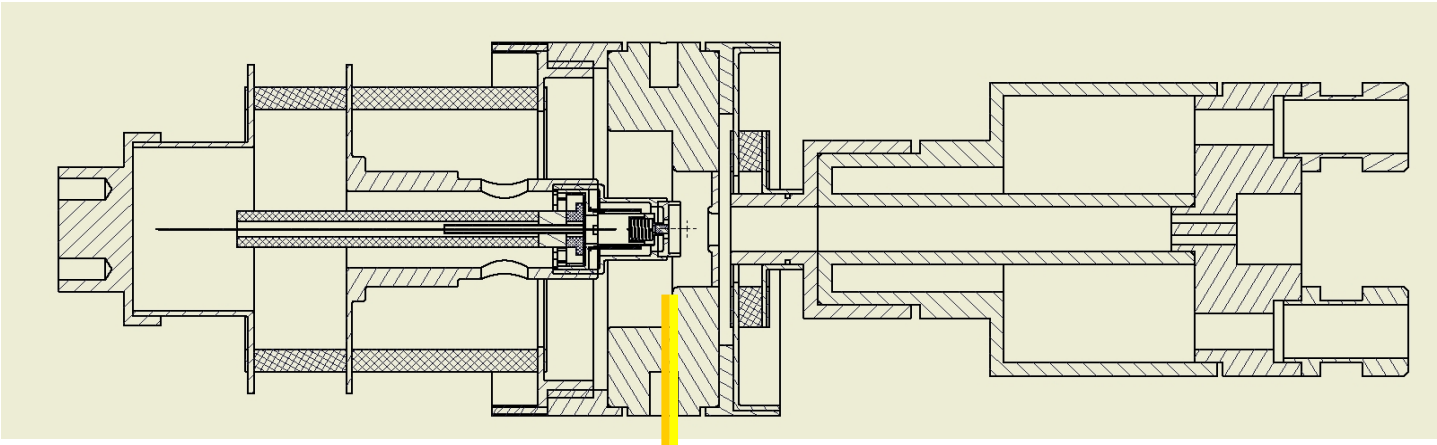
Vacuum Sublimation

Freeze Sublimation Method

Experiments

Manufacturing of cathodes and THz electron guns

Main Part: Terahertz Tube Structure
Cathode: Φ1mm, Flat on Top
Anode: No Refridgeration
Collector: Water Cooled

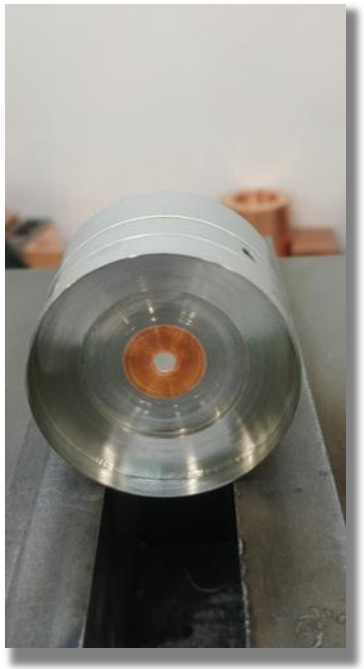


Insulated Cathode Assembly | **Anode/Collector (Short-Circuited)**

THz Electron Gun with High Emission Cathode (1mm)

Experiments

THz Electron Gun



Cathode Assembly → Anode Assembly → Leakage Detection → Baking

Experiments

Emission Test

Close-Spaced Diode Test Platform

Experimental THz Electron Gun

Results

Precursors and Active Substances

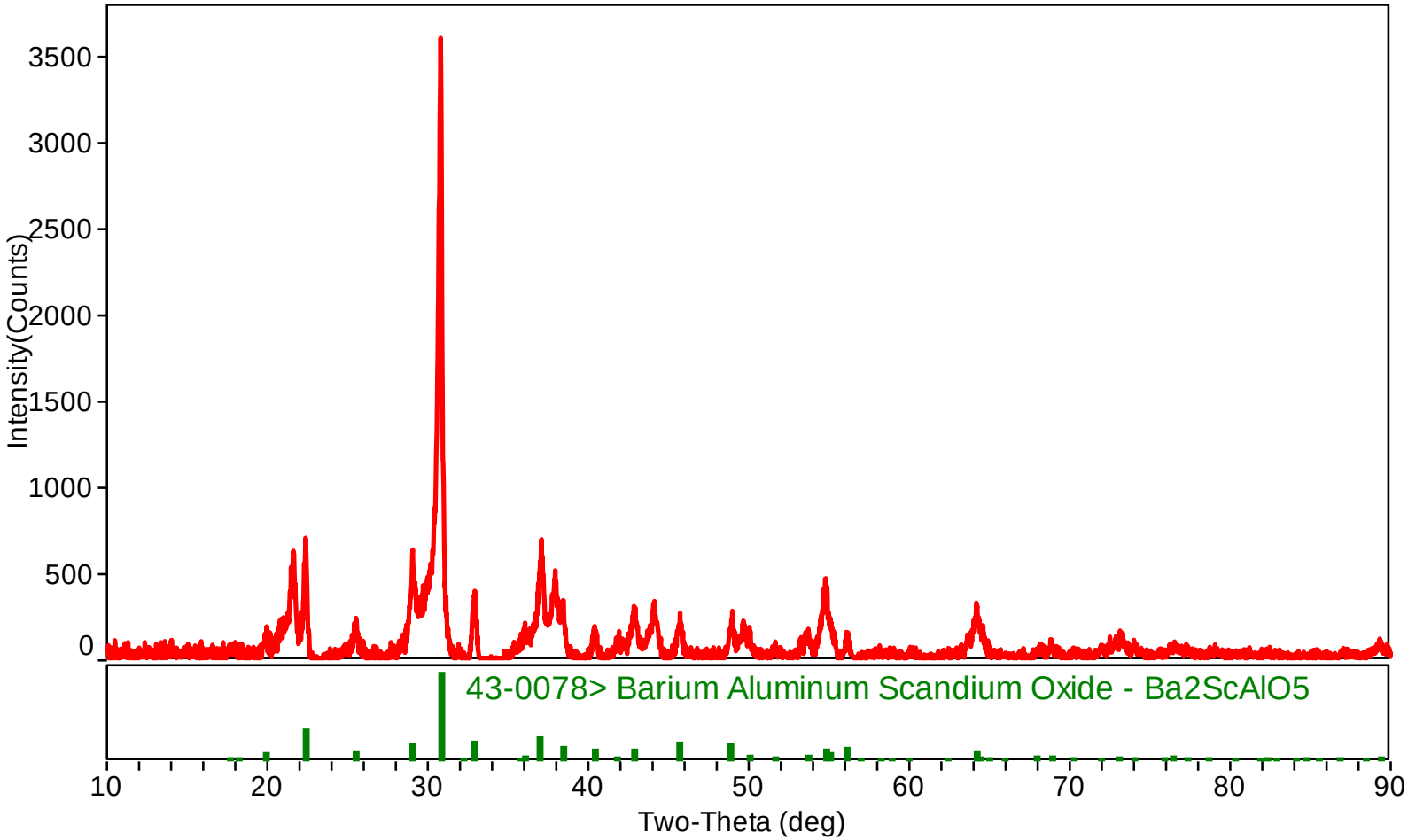
Sintering

Dry Precursor after Sublimation

Calcined Active Substance

Results

XRD Pattern Comparison



Almost Perfectly Consistent

Results

Melting Point

- **Novel active substances melts at 1730℃ under H_2 atmosphere, which is of importance.**
- **Impregnation of novel active substance can be arranged after brazing with Mo-Re filler and can be easily done in a conventional hydrogen furnace at 1750℃.**
  - **Mo-Re Brazing Temp:** 2000-2100℃ under H_2 atmosphere;
  - **411/612 Salts Impregnation Temp:** 1600-1800℃ under H_2 atmosphere.

- **Novel Substance can be used like 411/612 salts.**

Results

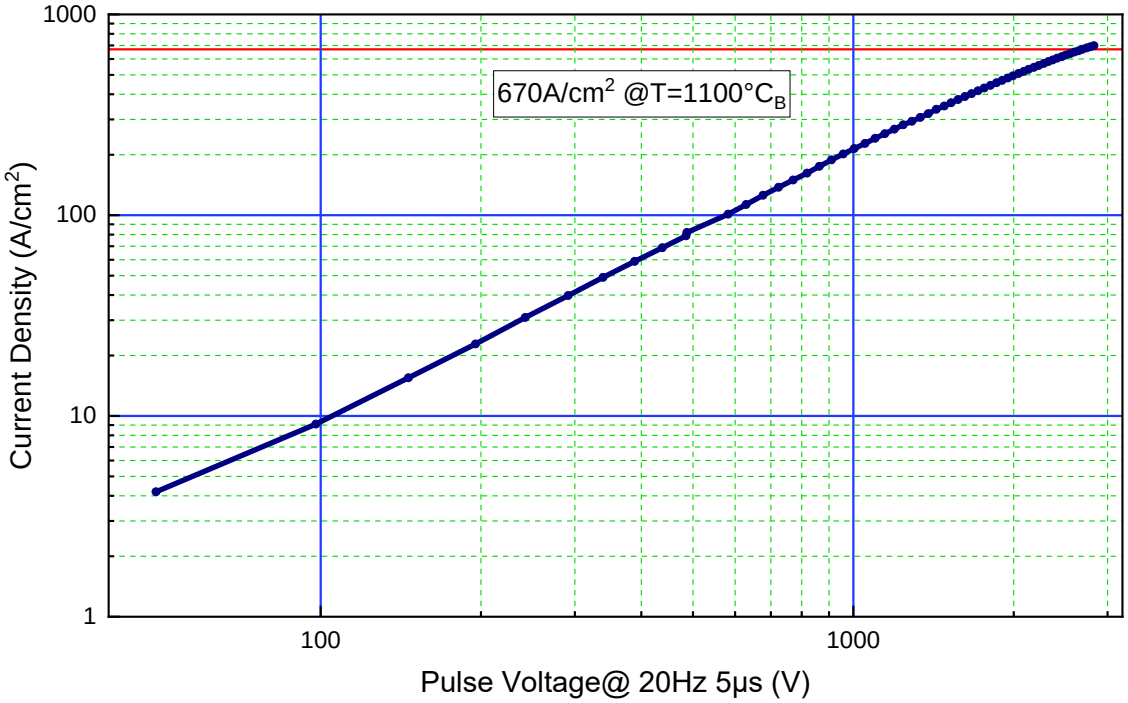
Pulse Emission Test

Water-Cooled-Anode Planar Diode

End Face Diameter: Φ1mm
No Retaining Ring

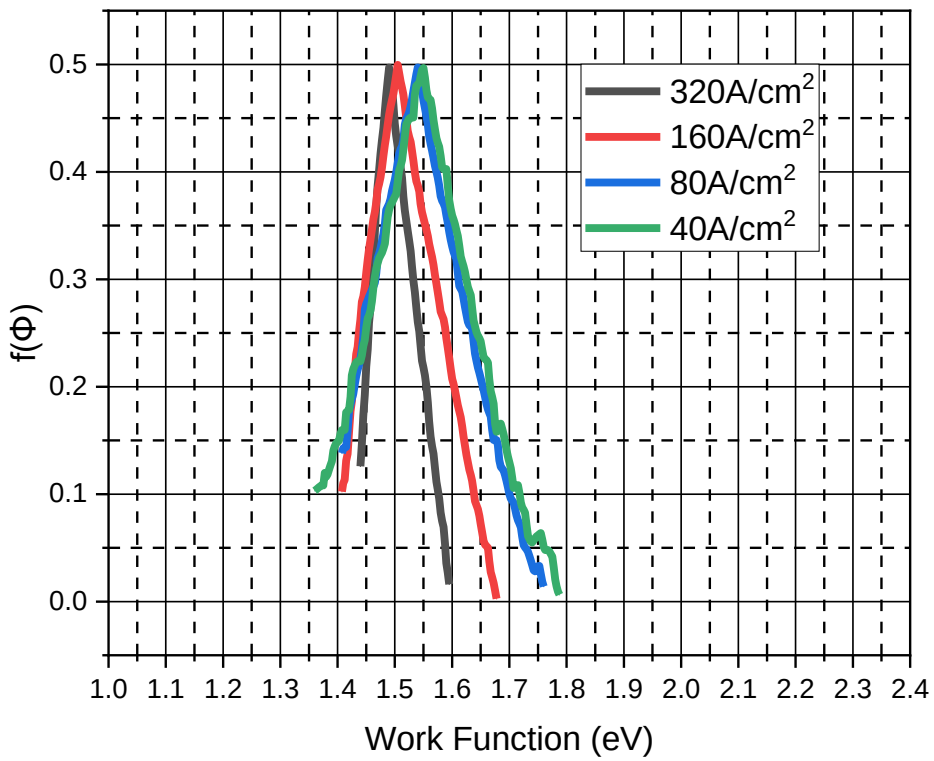
Frequency: 20Hz
Pulse Length: 5μs
Duty Cycle: 1/10,000
Temperature: 1100℃$_B$

Current Density: 670A/cm^2



Results

Practical Work Function Distribution (PWFD)



Peak Work Functions
320A/cm²: 1.490eV
160A/cm²: 1.505eV
80A/cm²: 1.540eV
40A/cm²: 1.550eV

Heavier the workload, Higher the electrical field intensity, Smaller the work function.

Results

Cathode's Performance in Electron Gun

Condition 1

Frequency: 20Hz
Pulse Length: 5µs
Duty Cycle: 1/10,000
Temperature: 1090-1100°C$_B$
Emission Current: 1.20A
Current Density: 152A/cm^2

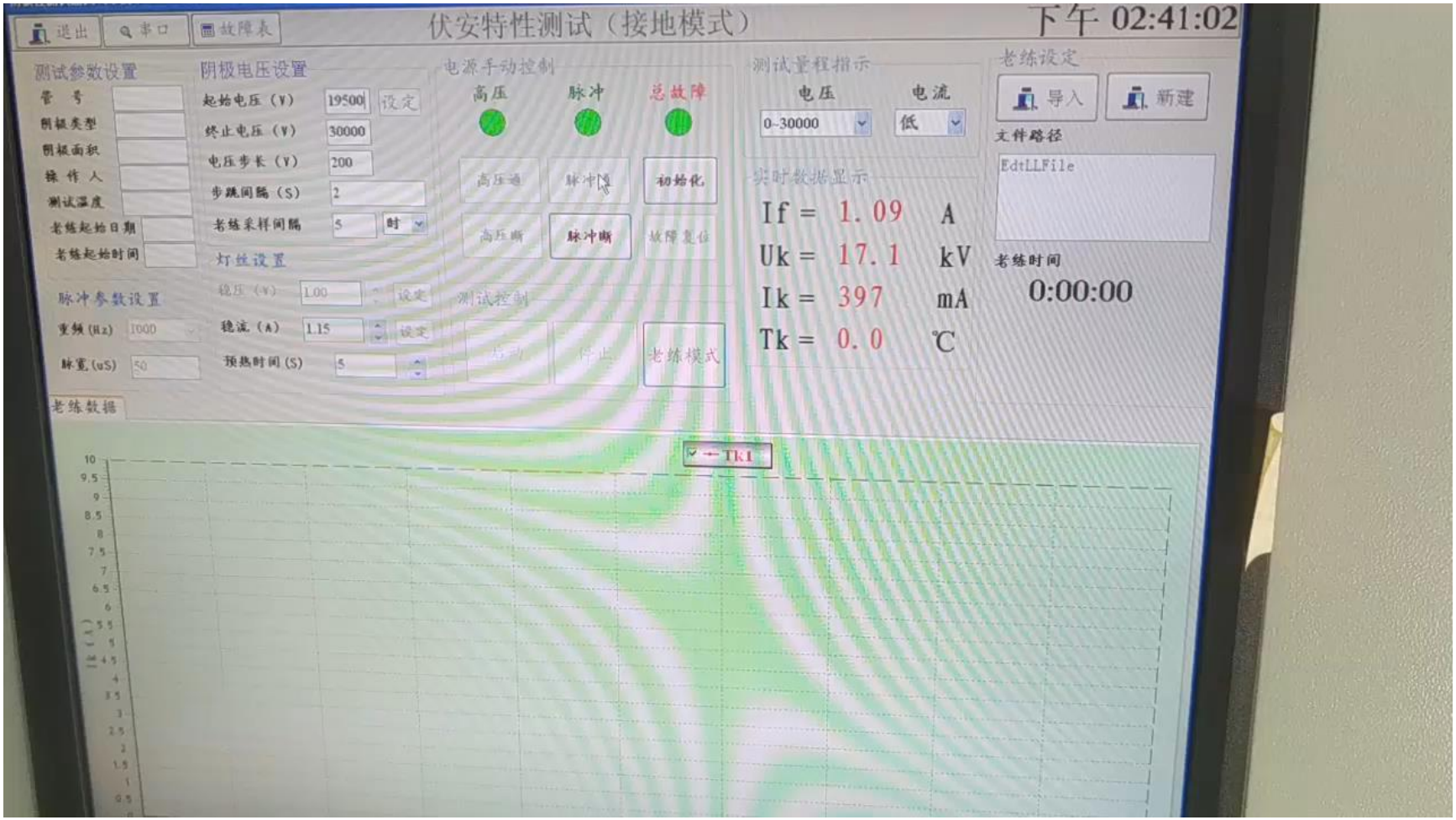
Condition 2

Frequency: 1000Hz
Pulse Length: 50µs
Duty Cycle: 5/100
Temperature: 1090-1100°C$_B$
Emission Current: 0.42A
Current Density: 53A/cm^2

Results

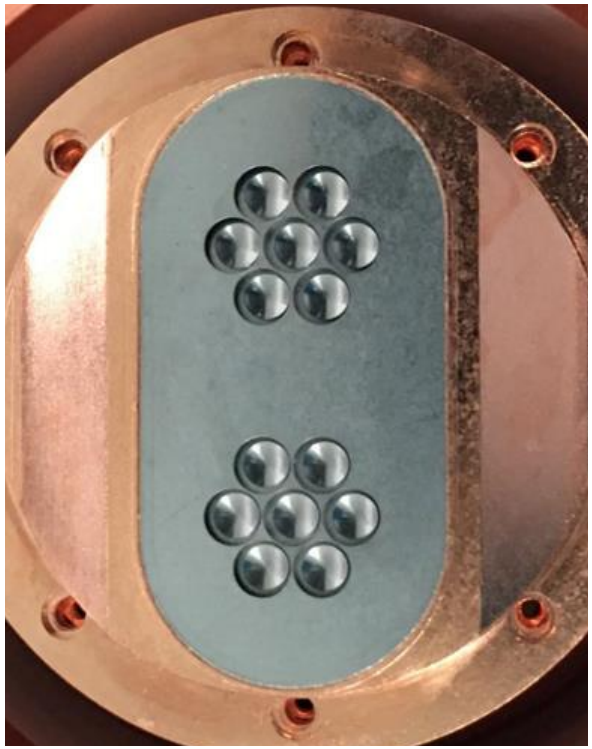
Electron Gun Emission Duration Test:

53A/cm² for 300 hours.



Results

Applications



X-Band Multibeam Klystron
Duty Circle=5%, Current Density 25A/cm^2
Temperature: 950-1000℃$_B$

New Model

Questions:

- **Why do scandate cathodes get much more emission than M-type cathodes or conventional dispenser cathodes?**
- **Why is Ba_2ScAlO_5 or Ba:Sc=2:1 the best?**
- **What is the essence?**

New Model

Based on our previous experimental foundations,

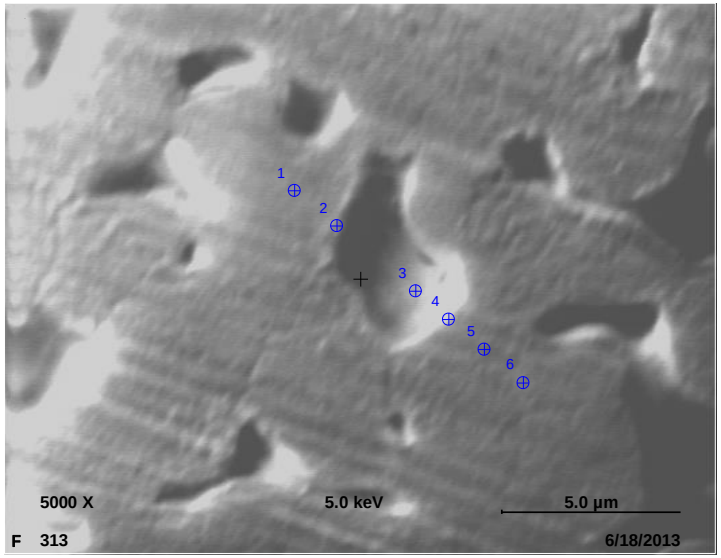
We put forward the **‘Binary Tree Model’**

Our Experimental Foundations

- **Elementary compositions of these 4 points on cathode's tungsten surface are very close or almost the same.**

Auger Electron Spectroscopy Results of High Emission Cathode

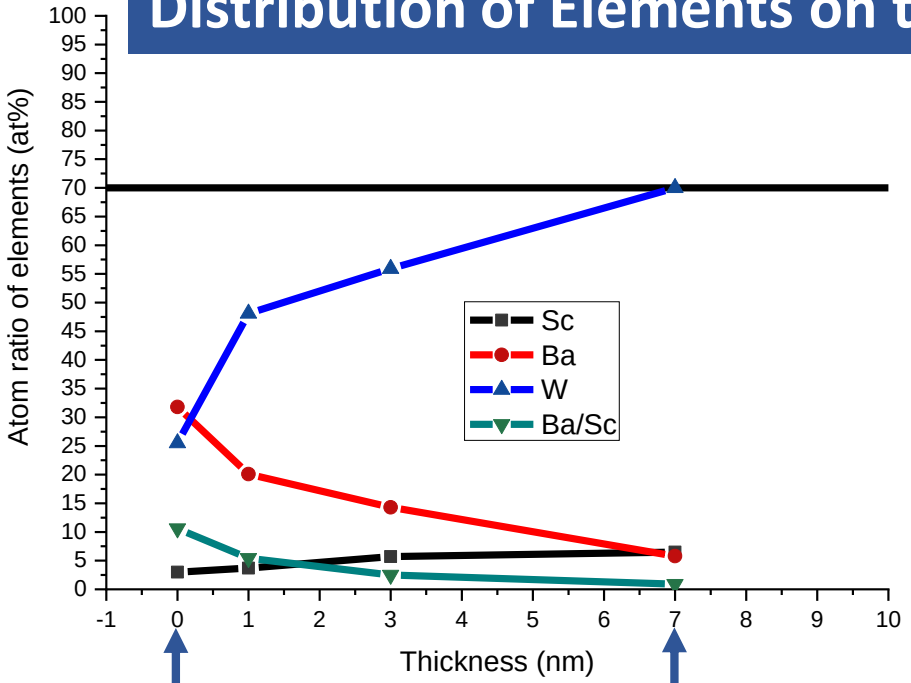
PHI-700 Nanometer Scanning AES System



Point number	Site (Distance to pore edges)	C1	O1	Al2	Ca1	Sc1	Ba3	W2	Atom ratio Ba/Sc
1	1.5µm	32.8	18.9	1.6	1.6	11.7	15.1	18.4	1.29
2	0	31.3	25.2	5.2	2.6	11.7	22.0	2.0	1.88
3	Center	28.3	24.8	3.9	1.4	9.2	31.1	1.4	3.38
4	0	31.1	20.3	4.5	1.0	9.7	19.1	14.4	1.97
5	1.3µm	32.5	19.3	2.9	1.1	11.5	15.2	17.7	1.32
6	2.8µm	30.4	19.3	3.3	1.2	11.9	17.9	16.1	1.50

Our Experimental Foundations

Distribution of Elements on the Cathode's Surface in Depth



- From top to bottom,Ba content goes from high to low, Sc content goes from low to high.
- When atom ratio of Ba to Sc in the active substance is 2:1, the cathode emission is maximized.

Previous Experimental Foundations

- Diferent atoms and their ions have fixed partical radius.

Particle Radius

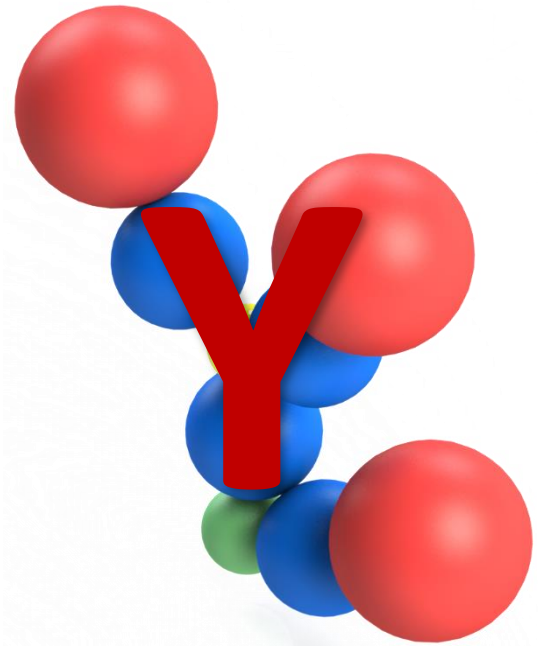
Ion	O^{-1}	O^{2-}	Sc^{+}	Sc^{2+}	Sc^{3+}	Ba	Ba^{+}	Ba^{2+}	W^{2+}	W^{3+}
Radius (Å)	0.93	1.21	1.36	1.09	0.73	2.24	1.79	1.34	0.80	0.75
Relative Radius	1.27	1.66	1.86	1.49	1	3.07	2.45	1.84	1.10	1.03

- Sc atoms alone can not emit directly.

Precondition for Model

- The entire emission structure is electrically neutral ;
- Base metal is $W^{2+}(a)$;
- $O^{2-}(a)$ is the only ion that adsorbs metal ions;
- $Ba^{+}(a)$ is the only ion which can emit and lies on the outmost layer of cathode surface;
- Sc can only has its natural +3 valence in the structure.

Binary Tree Model



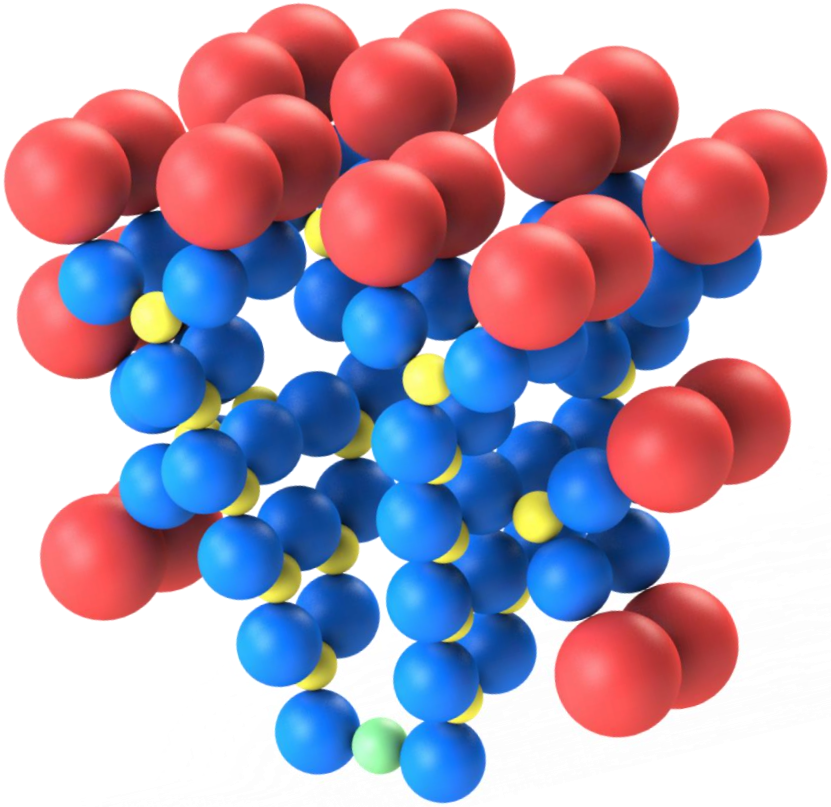
Basic Structure

- $W^{2+}(a)$ ion, as the root, ties up the $O^{2-}(a)$ branches.
- Sc^{3+} is bonded with three $O^{2-}(a)$- ions, serving as the joint points of 'Y' letter shape structure, which is like the fork of a tree.
- '$Ba^{+}(a)$-$O^{2-}(a)$-' pairs are the branches with emissionable fruits hanging on the top of surfaces.

(a) : adsorbing

$Ba^{+}(a)$ $O^{2-}(a)$ $Sc^{3+}(a)$ $W^{2+}(a)$

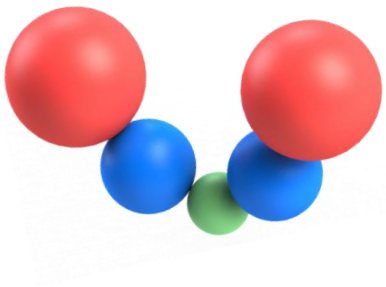
Binary Tree Model of Scandate cathode



Typical structure

- There are 16 Ba^{+} ions on the outmost layer, and 8 Sc^{3+} ions on the second outmost layer in height direction;
- Other 8 Ba^{+} ions and 4 Sc^{3+} ions are on the side branches;
- The total Ba:Sc molecular ratio is 24:12 or simpified 2∶1, which is perfectly consistent with that of our salt recipe.

Binary Tree Model on M-type cathode



M-type Cathode

Typical structure

- Only 2 Ba^{+} ions are on the outmost layer.

Scandate Cathode VS. M-type Cathode

Atoms of Different Structures

Atom	Ba	Sc	W
Scandate Cathode	24	12	1
Impregnated Cathode	2	0	1

The emission ability of the scandate cathode is a magnitude more than that of a M-type cathode.

With Binary Tree Model, what can we do?

May explain Sc's role in emission enhancement

- When Sc element exists in the inner layers of the cathode surface, it plays an important and special role: Sc ions as junction or bifurcation points can greatly extend the network and support more Ba ions to grow on the top of the cathode's surface ;
- Scandate cathodes have much more Ba^{1+} ions on the surface of cathode , a magnitude more than those of M-type cathode!
- Sc alone can not emit, but it turns 'a single shot pistol into a shotgun'!

Summary

- As an innovative active substance, Ba_2ScAlO_5+3at%SrO, whose melting point is 1730℃, can be easily used like 411 or 612 salts.
- The cathode (Φ1mm, without retaining rings), which was impregnated with the new active substance, showed an emission current density of 670A/cm^2 in planar diode test (20Hz, 5μs, 1100℃$_B$), and reached 152A/cm^2 in a THz electron gun tube (20Hz, 5μs, 1090℃$_B$).
- Binary Tree Model was put forward, which may be used to explain the special role of Sc in emission enhancement.
- The high emission performance and good operability of the new substance and cathodes show that our idea may provide a very promising cathode option for terahertz and other new devices.

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Xinping Lv

Zhipeng Lu

Feng Ren

Thank you!

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- In height direction, there are 5 layers of Sc ions;
- There are 2, 4, 4, 4 and 8 Sc ions in these layers respectively from bottom to top;
- Side branches take root in the 4th layer and have 4 Sc ions in total.