Flexible Packed Stencil Design with Multiple Shaping Apertures for E-Beam Lithography

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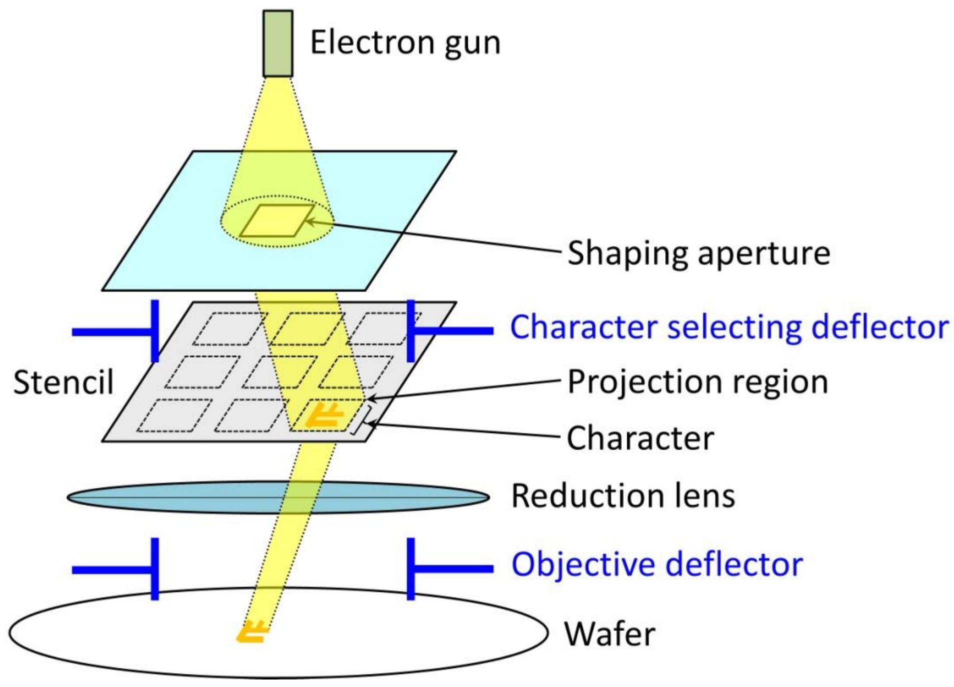
Introduction

- Next generation lithography solutions being actively pursued (EUV, e-beam, directed self-assembly, nanoimprint).
- Uses of e-beam
  1. For mask writing
  2. E-beam direct write
     - directly write on wafer
     - avoid ever-increasing mask cost
     - has very high resolution and no depth of focus problem
- Our objective: maximize e-beam writing throughput

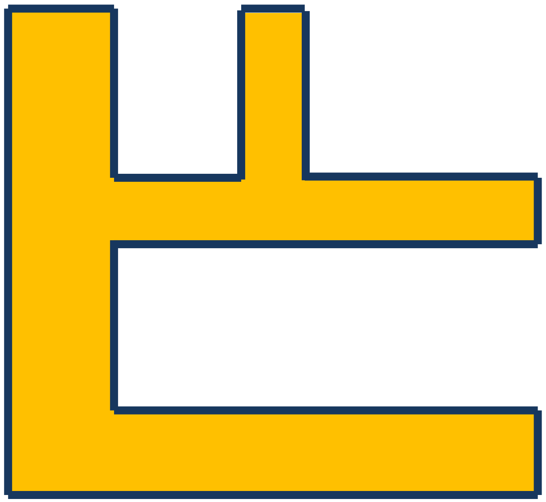
E-beam Writing with Character Projection

- Character projection method
  - Patterns that occur many times in a die are made into a set of characters on a stencil
  - Then one shot can print a complex pattern rather than a single rectangle

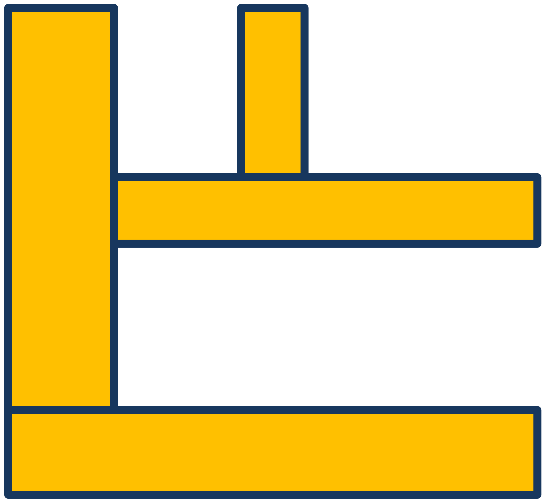


Character Projection Reduces Shot Count

(a)



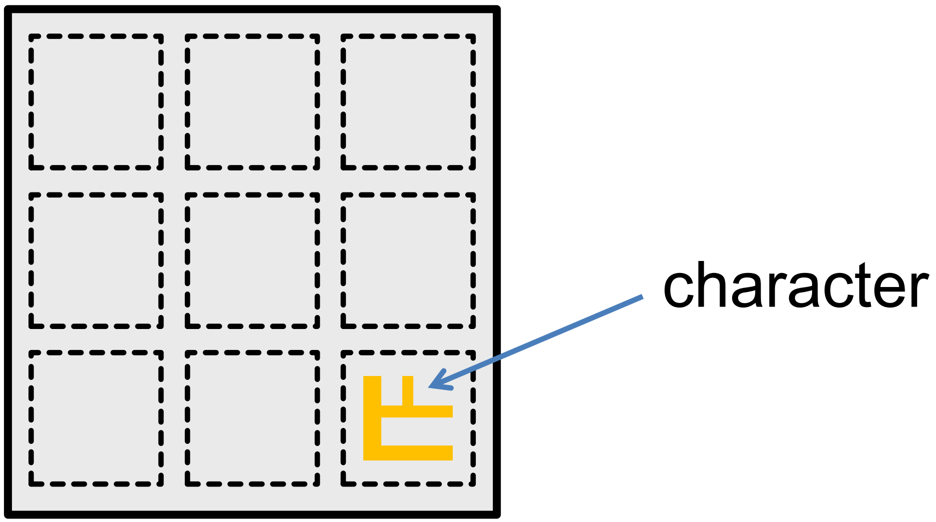
(b)



(a) As a character on the stencil, the whole pattern can be printed in 1 shot.

(b)Otherwise, requires 4 shots using variable-shaped beam (VSB) mode.

Traditional Stencil Design

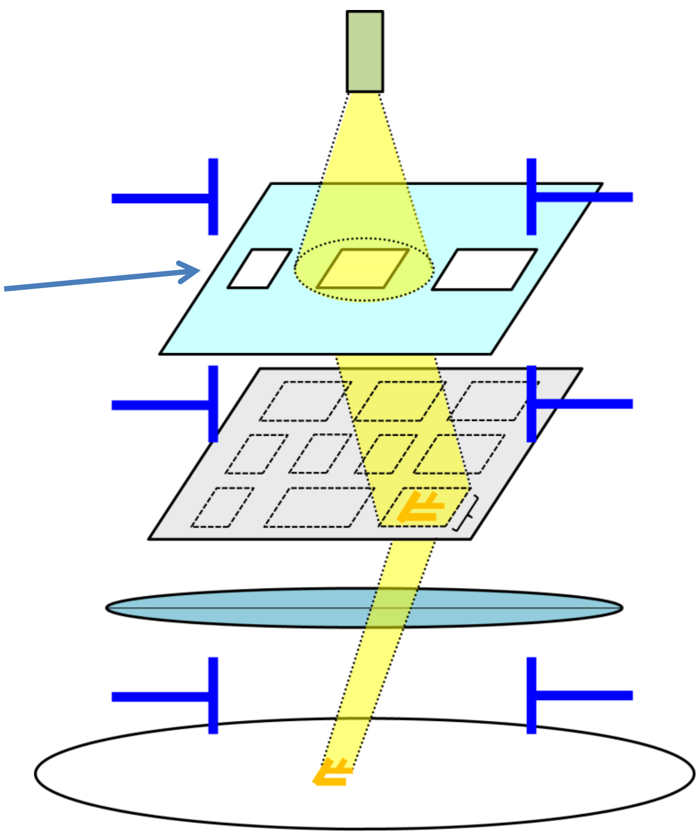


- Stencil size is limited.
- Traditionally, stencil as a 2D-array for holding characters.
- Pick and place the *N* most beneficial characters into *N* pre-designated spots on the stencil.

Flexible Packed Stencil Design w/ Multiple Shaping Apertures

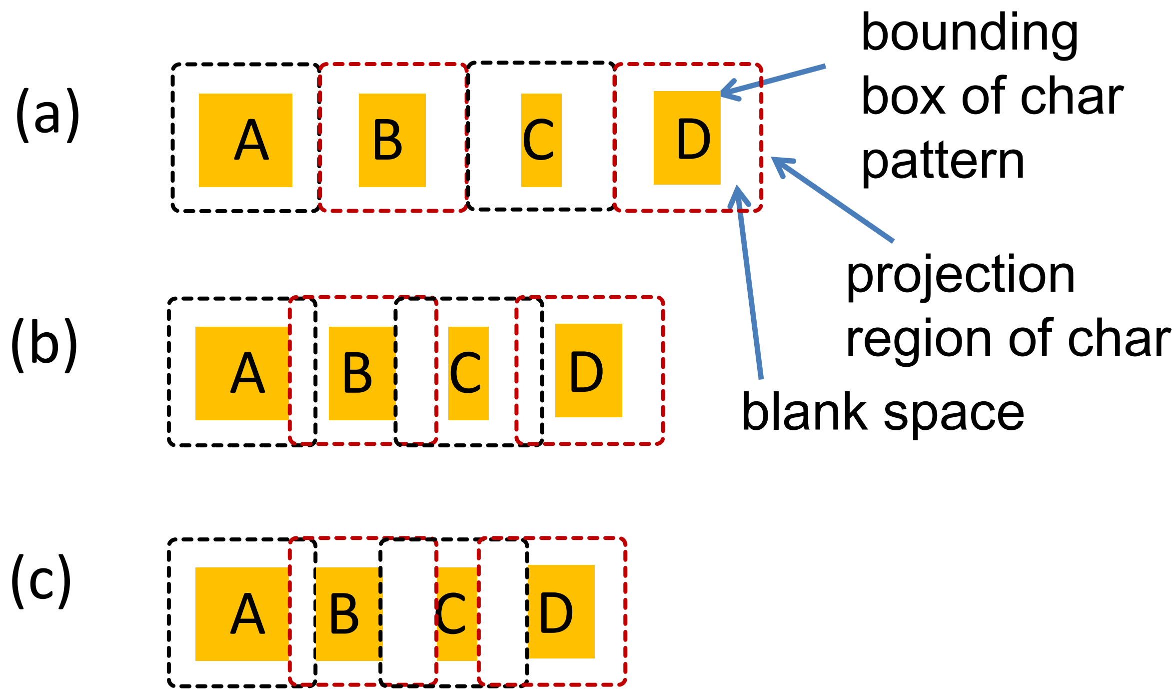
- Increase # chars on stencil by
  - using multiple shaping apertures (smaller characters can use smaller shaping apertures)
  - flexible bank space sharing

3 different sized shaping apertures



Flexible Packed Stencil Design w/ Multiple Shaping Apertures

- Flexible blank space sharing packs characters in the smallest space.



(a) Traditional packing of chars on a stencil.
(b) Previous works pack chars in smaller space.
(c) Our work pack chars in the smallest space.

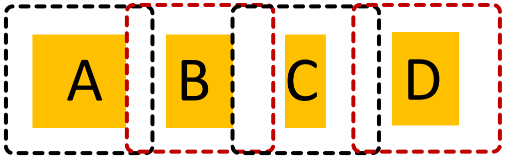
Problem Formulation

- Given
  - *K* : # of shaping apertures allowed
  - *C* : set of char candidates for a cell-based circuit (each char corr. to a particular orientation of a standard cell)
  - Dimensions of stencil
- How to
  - determine optimal widths for the *K* shaping apertures
  - choose an optimal subset of chars from *C* and flexibly pack them on the stencil w/ blank space sharing

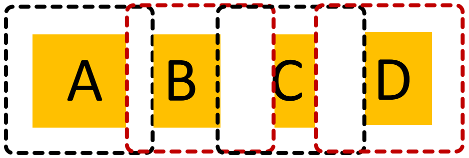
in order to minimize total shot count for printing the circuit?

Good and Bad News

- Bad news
  - Flexible packed stencil design is NP-hard.
- Good news
  - Tight linear packing is near optimal and can be computed efficiently.



Non-tight packing



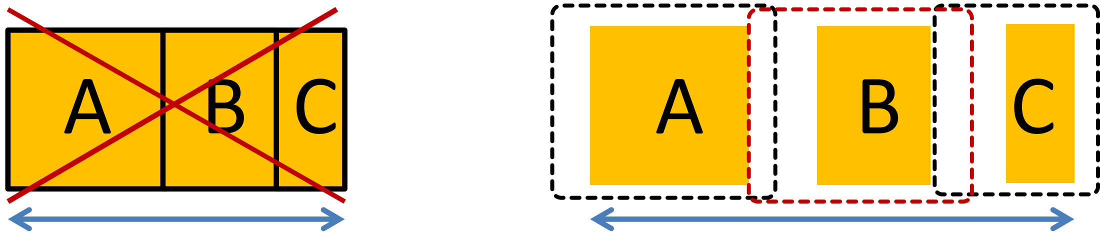
Tight packing
(blank spaces of adjacent chars completely overlap)

Our Algorithm

1. Determine *K* projection region widths & select a subset of chars to be put on stencil by dynamic programming.
2. Assign chars selected in Step 1 to rows on the stencil & construct a tight linear packing for each row.
3. Greedily pack some of the unselected chars at the end of each row, if possible.

Challenges for DP Formulation

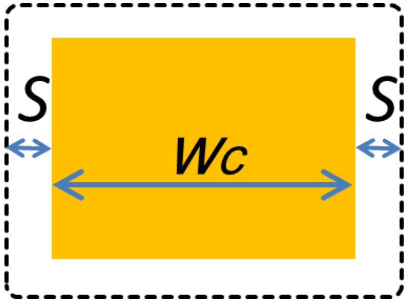
- O($2^{|C|}$) runtime and memory requirement just to determine whether to include each char in stencil.
  - $|C| > 1000$ (over 1000 cell types used in a circuit)
- Want to simultaneously determine the projection width used by each chosen char s.t. # different projection widths used ≤ K.
- Width consumed by a set of chars is not equal to their total width (also depends on projection width used by each char & amount of blank space sharing).



Useful Properties

- Let w_c be the width of char c.
- Let S be the safety margin.

1. Projection width for char c must be $\geq w_c + 2S$

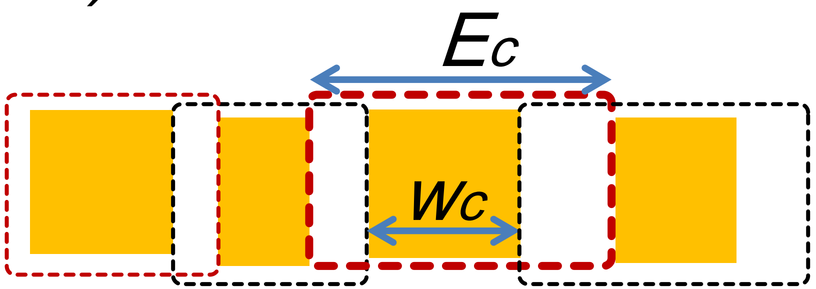


2. To choose K optimal projection region widths $e_1, \ldots, e_K$, suffice to consider $e_i = w_c + 2S$ for some c. (# distinct widths in a cell library is limited.)

Useful Properties

- Let E_c be the projection region width used by c.

3. Effective width of c in a tight linear packing is
   $w_c + (E_c - w_c)/2 = (w_c + E_c)/2$



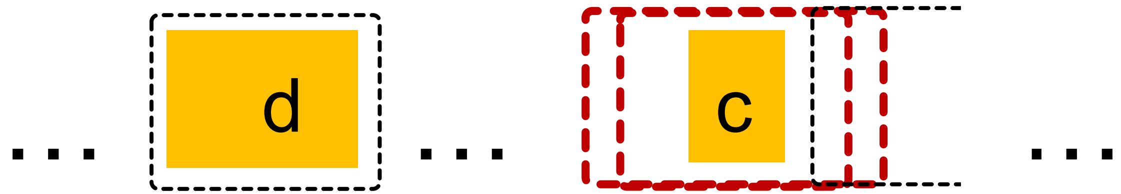
4. If m chars are ordered s.t. $E_i - w_i \leq E_{i+1} - w_{i+1}$ for $i = 1, \ldots, m-1$, then a tight linear packing can be constructed in that order.

   Proof: By induction

Useful Properties

5. There exists an optimal solution s.t.
   $w_c \leq w_d \Leftrightarrow E_c \leq E_d$

   Proof:



6. For chars with same width, one that produces a higher shot saving should be included in stencil with higher priority.
   – Shot saving of including char c is $r_c(n_{VSBc} - 1)$ where
     r_c = # times c appears in the circuit
     n_{VSBc} = # shots to print c by VSB

Our DP Formulation

- Take advantage of these properties.
- Character Grouping technique
  - Avoid considering each char separately.
  - Group all chars according to width.
  - Sort chars in each group in decreasing shot saving.
  - For each group G, there are only $|G|+1$ possible choices (i.e., include first i chars of G where $i = 0$ to $|G|$)
  - Process the groups in decreasing order of their char widths (so no group ever use a projection width larger than that of a previous group).

Experimental Results

- Benchmarks
  - 1D-1 to 1D-4 (1000 chars each) from E-BLOW in DAC'2013
  - 1D-1h to 1D-4h (1200chars each)
- Stencil size: 1000μm X 1000μm
- Memory requirement
  - without character grouping technique, >18GB in some cases
  - with character grouping technique, < 0.5GB in each case
- Maximum runtime ~40s (Linux server w/ 2.67GHz CPU)

Experimental Results

	E-BLOW #shots	E-BLOW #chars	Ours (K=1) #shots	Ours (K=1) #chars	Ours (K=2) #shots	Ours (K=2) #chars
1D-1	29536	934	12972	980	10418	**1000**
1D-2	44544	863	28594	895	10418	**1000**
1D-3	78704	758	55761	797	30785	902
1D-4	107460	699	79275	734	44468	837
Normalized	1.65	0.955	1	1	0.57	1.102

	Ours (K=1) #shots	Ours (K=1) #chars	Ours (K=2) #shots	Ours (K=2) #chars	Ours (K=3) #shots	Ours (K=3) #chars
1D-1h	58648	980	26467	1114	17534	1163
1D-2h	86176	905	48891	1018	39630	1068
1D-3h	135332	800	93109	916	75709	948
1D-4h	169105	739	116219	855	98204	886
Normalized	1	1	0.598	1.141	0.475	1.188

Conclusions

- Developed an efficient algorithm for flexible packed stencil design w/ multiple shaping apertures by taking note of several useful properties.
- # e-beam shots to print a circuit is greatly reduced by
  - Selecting optimal shaping aperture size(s)
  - Using multiple shaping apertures
  - Flexible blank space sharing
- Directly applicable to multi-beam direct write system.